Volume XXXIII March-April 1938 Number 2

# Economic Geology

and the

## Bulletin of the Society of Economic Geologists

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# ECONOMIC GEOLOGY

VOL. XXXIII MARCH–APRIL, 1938 No. 2


## BRIEF GEOLOGICAL NOTES ON CERTAIN PRE-CAMBRIAN MINING AREAS IN NORTHERN AUSTRALIA.


E. C. ANDREWS.


IN A recent editorial, the scope and aim of the " Aerial, Geological, and Geophysical, Survey of Northern Australia " was outlined. During the course of that Survey, various mining fields were examined, some among them being already well known, others, however, such as the Tennant Creek Gold Field, being very imperfectly known; and others, again, such as the Claudie River Gold Field, being practically new.

The attached outline map indicates the general location of the main areas examined.

Brief notes on the general geology of several important mining areas are given in this article, as being typical of the structure of the vast pre-Cambrian formations of the portion of Australia being examined by the Survey mentioned above. Broken Hill is not within the area under consideration, but a brief reference to that field is included also because of the light which a study of its well-known structure may be expected to throw upon the pre-Cambrian structures lying farther north. Gustaffson's excellent account of the Kalgoorlie Field, in a recent number of ECONOMIC GEOLOGY, is recommended to the attention of students of the pre-Cambrian mining fields of Australia.

It is hoped that a statement, even if incomplete, concerning the geological structures of the newer fields of Tennant Creek and the Claudie River may be acceptable to readers generally. The writer has not made a personal examination of these two fields,

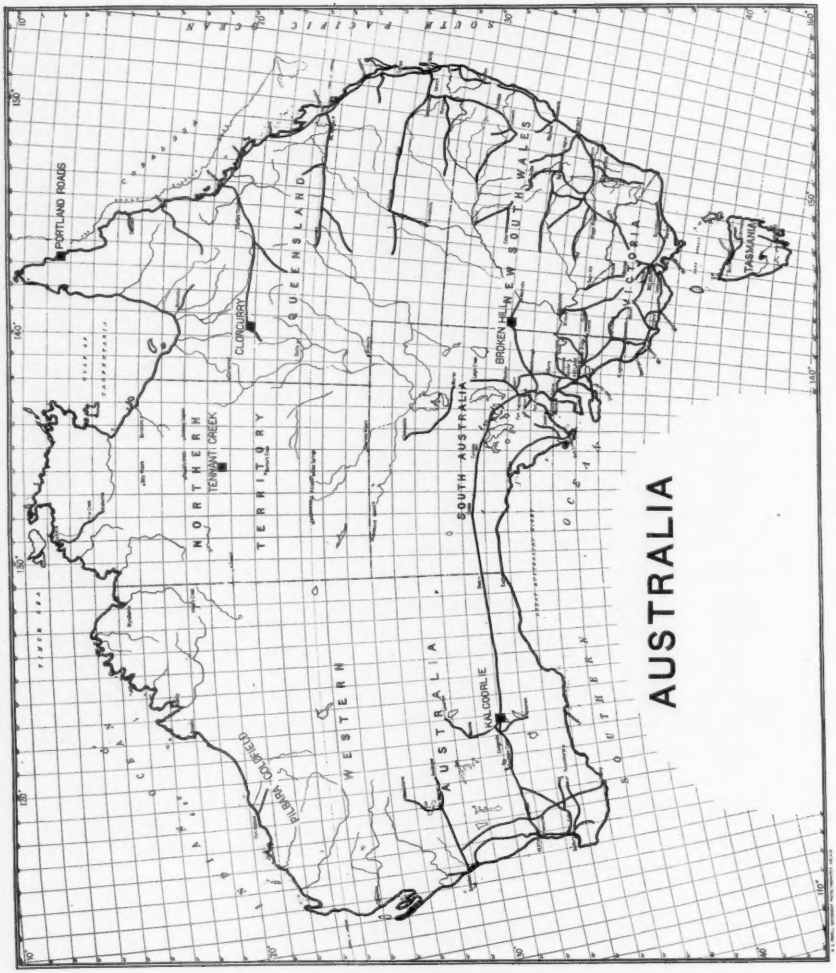
AUSTRALIA
PORTLAND ROADS
CLONCURRY
TENNANT CREEK
NORTHERN TERRITORY
QUEENSLAND
WESTERN AUSTRALIA
SOUTH AUSTRALIA
NEW SOUTH WALES
BROKEN HILL
KALGOORLIE
COOKTOWN
PILBARA
TASMANIA
VICTORIA
SOUTHERN OCEAN
SOUTH PACIFIC OCEAN

FIG. 1.

but has simply reviewed the official information recently obtained, in the light of a somewhat detailed knowledge of other pre-Cambrian fields in Australia, such as Broken Hill. As an introduction to the notes on these two areas, the general geological associations at Pilbara, Cloncurry, and Broken Hill are supplied.

FIG. 1.

## PILBARA (WESTERN AUSTRALIA).

Four great rock formations occupy this extensive field, namely, the Warrawoona, Mosquito Creek, Granitic Intrusive, and Nullagine, Series. The naming of these groups is as from older to younger. All are pre-Cambrian.

The Warrawoona Series comprise quartzites, jasperoids, chloritic and chlorite-magnetite schists, with contemporaneous basic and siliceous lava flows, all highly folded. Their prevailing strike is northwest. In general they are compared with the Kalgoorlie Series, lying a considerable distance to the south, and which include contemporaneous lavas and slates, overlain by "slates," altered "tuffs" and grits, and associated with a sill or lacolithic form of "greenstone" inserted between the older lavas and overlying sediments mentioned above.

The relationship of the associated Mosquito Creek Series with the Warrawoona is not known definitely, but, by some observers,[1] they are considered to be separated therefrom by an unconformity.

The main rock types comprise closely-folded slates, phyllites, jaspillites, and quartzites, whose dominant strike is N. 80° E. approximately. Granitoid rocks occupy a considerable area of the Pilbara district, and these have intruded the Warrawoona and Mosquito Series alike. These granitoids are reported to have been the main source of the Pilbara mineral deposits.

The members of the Nullagine, or late pre-Cambrian, Series, lie subhorizontally, or with very gently rolling dip, on the profoundly eroded series mentioned above. This young group is composed, mainly, of unaltered conglomerates, quartzites, and contemporaneous lava flows.

[1] David, T. W. E.: Explanatory notes on a geological map . . . of Australia. Commonwealth Council Sci. and Indus. Research, pp. 31–32. Sydney, 1932.

The main mineral deposits of the Pilbara area consist of gold, copper, lead, tin, tantalite, and asbestos. These, with the exception of the tin and tantalite, occur in the Warrawoona; the tin occurs in the granite, and the tantalite in pegmatitic dikes.

### CLONCURRY DISTRICT (NORTHWESTERN QUEENSLAND).

In this field, both pre-Cambrian and Cambrian formations are well represented, all being concealed, in some measure, by gently-undulating Cretaceous sediments and still younger laterite, travertine, and alluvial, cappings.

The pre-Cambrian rocks are classified by the Queensland official geologists as "Archæozoic" and "Proterozoic." The "Archæozoic" associations have been divided into an older or Kalkadoon-Argylla Series, and a younger, or Soldier's Cap, Series, corresponding respectively, according to the official belief, to the ancient Yilgarn Series of Western Australia and the Kalgoorlie-Warrawoona of the same state.

The "Proterozoic" is divided into the Mount Isa and Mount Quamby Series, these being compared, respectively, with the Mosquito Creek and Nullagine Series of Western Australia. In the absence of detailed connecting areal surveys it will be evident that these lithological correlations are only tentative.

The Kalkadoon-Argylla Series includes a belt, thirty to forty miles in width, of paragneisses, amphibolites, and gneissic granite, with a strike approximately meridional. These carry the more important copper deposits of the district.

The Soldier's Cap Series consists of ". . . schists, fine, grained greenstones and quartzites. The greenstones are lava flows interbedded with slates and quartzites, and have, in places, a characteristic ropy structure. . . ." Both Soldier's Cap and Kalkadoon-Argylla groups have been intruded by granitoids, both also being strongly metamorphosed regionally in addition to evidencing local contact phenomena.

The Mount Isa Series, occupying the western portion of the Cloncurry district and possessing a strike, approximately meridional, consists of conglomerates, quartzites, red and purple

shales, limestones, and "greenstones" (basic lavas with amygdaloidal structures). The Mount Isa rock types are considered to be younger than the groups above mentioned by reason of the lack of regional metamorphism within them at the granite contacts, and because of the absence of proved intrusive granitoids.

The Mount Quamby Series consist of arkose, conglomerate, and sandstone, beds, arranged horizontally or with gently-undulating dip.

The Cambrian (Lower, Middle, and Upper) sediments, containing a rich trilobite fauna, consist, in great measure, of limestones and siliceous shales disposed horizontally or in gently-undulating fashion.

Compression has produced, in the sediments of pre-Quamby age, a marked meridional strike, and a series of shear-zones parallel to the strike of the sedimentary folds. Overthrusting has been observed.

The ore bodies in every instance are closely associated with the structural features. Speaking generally, the gold deposits proper occur in the highly-folded pre-Cambrian rocks in fracture zones in proximity to a granite contact. Gold, moreover, is associated with most of the copper ores, which occur both as overlapping lenses in shear zones, parallel to the strike of the "country," and as deposits in fault zones which are arranged almost at right angles to the lenticular deposits of the shear zones.

Silver-lead deposits are represented, principally, by the "Mount Isa Lode," which is stated to be a tabular deposit in shales characterized by remarkable "ribbon structures." The deposit is a replacement type, consisting of alternating bands of ore and "country rock."

### BROKEN HILL (WESTERN NEW SOUTH WALES).

Broken Hill, similarly to the Pilbara, Kalgoorlie, and Cloncurry, areas, contains various pre-Cambrian formations, some being intensely-folded and metamorphosed, others exhibiting much less evidence of folding and alteration. Early, but unfossiliferous, formations, rest subhorizontally, or in gentle undula-

tions, upon the deeply-eroded pre-Cambrian formations, and Jurassic, Cretaceous, and Tertiary, horizontal outliers, are common in the outlying district.

The oldest series is known as the Willyama, and consists of various types of shale, mudstone, sandstone, and contemporaneous basic lavas, which have been intruded by granitoids and pegmatites, all being intensely folded and metamorphosed—the sandstones, shales, and mudstones to quartzites and garnet-sillimanite-biotite-feldspar-gneisses, the granite to augen-gneiss. Deposits of silver-lead-zinc, platinum, tin, wolfram, and other materials, are common, the silver-lead-zinc deposits occurring in great measure either as replacements of the ancient mudstones and shales, or as lenses in the the drag-folds or zones of crush; the tin and wolfram occur as overlapping lenses in crushed zones with pegmatite following the general directions of the ancient bedding planes. The platinum is closely associated with serpentine occurrences which are arranged parallel with the strike of the containing sediments.

The later pre-Cambrian and early Palaeozoic sediments in the Broken Hill district proper are lacking in mineral deposits, nevertheless in the outlying districts where the late pre-Cambrian sediments have been strongly folded, deposits of copper and other minerals have been worked in a minor way.

### TENNANT CREEK GOLD FIELD (NORTHERN TERRITORY).

This field is situated in the arid country lying between Lat. 19° and 20° S., and surrounding the Tennant Creek Telegraph Station on the Overland Telegraph Line connecting Adelaide with Port Darwin. The rock formations are reported to be pre-Cambrian in age. According to Woolnough[2] they consist "dominantly of talcose, chloritic, micaceous, graphite (?), and siliceous, schists, with considerable amounts of interbedded schistose quartz-porphyry in places." Granitoid intrusions of pre-Cambrian age are recorded, and a granitic type occupies a considerable area in the northern and north-western portion of the

[2] Woolnough, W. G.: Report on Tennant Creek Gold Field, N. T. Bull. 22, 1936. Govt. printer, Canberra, F. T.

field. The ancient sediments have been folded and considerably altered, the strike of the folds being, approximately, east and west. Schistosity is pronounced, the main axis of this being almost east and west.

The general topography is that of a plain surmounted by a number of subparallel hill ridges possessing a vertical relief of two hundred feet, approximately, above the general level. The ridges represent the harder rock belts and the ore deposits occur mainly in these more resistant masses.

The ore bodies themselves consist, mostly, of lenticular masses of specular iron or hematite, intimately intergrown with magnetite, the lenses having developed in zones of crushed sediments, the strike of these "mineral" zones sympathising with the general trend of the sedimentary folds (as with so many of the deep-seated mineral deposits of pre-Cambrian age around Broken Hill and other localities in Australia). Quartz and "hematite" intergrowths are common also, and minor occurrences of sulphide ores are not unknown.

In form and size these mineral deposits vary considerably, namely, from mere blebs to masses 300 feet long and 30 feet in width. They occur in overlapping manner, within the crush or drag-fold zones. Presumably their vertical dimensions are comparable with their lengths. "Pipe" or "chimney" forms occur also, together with wall-like masses. Sheet forms, both vertical and subhorizontal occur, following the bedding planes of the original sediments.

Individual massive ironstone deposits appear to possess a sheath or casing of what is described as crushed "country rock" material containing "hematite" (hematite with magnetite) fragments; slickenside phenomena are abundantly present in these sheaths. Gold deposits occur in the sheathings, as well as in the "ironstone" masses themselves. Large and small masses of quartz and jasper occur abundantly also; these may be almost pure, or they may be intimately admixed with each other and with the hematite and magnetite.

As a general rule the quartz itself is not an ore carrier, the

gold being associated, characteristically, with the "black ironstone" masses. Transverse shear zones occur, which, at first glance, appear to be subordinate in general importance to the main east-west schistosity. On the other hand, as Woolnough suggests, it is highly probable that they are quite important in the deposition of gold values. In certain occurrences these transverse zones pass across the whole main zone of crush, while, in other places, they pass insensibly into the main shear zone. The latter type of occurrence with its "drag" phenomena is considered to be more favorable for gold prospecting than the complete cross fracture. The cross channels may contain quartz with abundant "hematite," coarsely crystalline, while the main body may be, essentially, a dense finely-grained mass of hematite and magnetite. This recalls the occurrence of the "garnet-magnetite" lodes of Broken Hill, where "lodes" of finely-granular garnet and magnetite (with some intimate intergrowths of quartz, zinc spinel, galena and zinc blende) occur within the area of the most intensely altered sediments (sillimanite-garnet-biotite gneiss), whereas, some miles distant from the centre of the old "hearth" of metamorphism, these lodes, which follow the sedimentary strike, have lost the finely-granular texture and have passed into masses of quartz of mural form containing magnetite coarsely crystalline in nature. Copper and bismuth occur also, but in minor amounts, at Tennant Creek.

The hematite (with magnetite) quartz, and jasperoid masses, appear to represent the action of heated and highly-penetrating emanations escaping from pressure and undergoing deposition, in great measure as replacements at various distances from their point of escape from a magmatic source, the whole group of reactions taking place under conditions of enormous load (great thickness of overlying sediments). Profound erosion alone has revealed the existence of these end products of ancient abyssal laboratories. In many mining fields in Australia, great replacement bodies appear to have resulted from the action of emanations given off from a heated source under an enormous thickness of cover. Excellent examples are the Broken Hill, Mount Isa, Mount Lyell, Cobar, and Canbelego, fields.

The accompanying summary account of the geophysical survey carried out at Tennant Creek until the close of 1936 has been prepared for this note by J. M. Rayner (Consultant Geophysicist):

*Tennant Creek.*—It has been shown that the gold values on this field are intimately associated with ironstone bodies. Many of these bodies outcrop and are at present being mined. The nature of their occurrence gave reason for supposing that others lay at various depths beneath the surface. There appeared thus to be scope for determining the position of these concealed bodies by means of the magnetic method of prospecting.

An area of nine square miles, approximately, has been examined closely, the most important area being the Mount Samuel, Eldorado, Cat's Whiskers' line, the Peko-Golden, Forty-Great Eastern line, the Wheal-Dorea-Peter Pan-Big Ben line, and the Rising Sun area.

Two chief types of magnetic anomaly were found, the one arising from superficial causes, the other from a deep seated origin. Twenty-four anomalies of the latter type have been discovered, and there can be no doubt that each indicates the presence of a concealed ironstone body of considerable size. Calculations show that their depths beneath the surface range from about 100 to 800 feet.

The geophysical work is being followed by a diamond drilling campaign (by the Northern Territory Administration), one hole being put down on each anomaly in the first instance. At a later date more intensive testing of the more favorable anomalies is to be undertaken. Four holes have been drilled already, each of which has penetrated ironstone as predicted. Low gold values were found in the cores and sludges; in the No. 3 hole however, very encouraging results were obtained, where sludges from 160 to 168 feet assayed 10.5 dwt. of gold per ton.

The magnetic prospecting campaign of the Tennant Creek field has proved a marked technical success, and it now appears likely that a definite economic success will be achieved. The results of the survey, whose predictions have been generally verified by drilling, throw much light on the nature of the ore occurrences and show that there are potential ore bodies on the field at greater depths than had hitherto been suspected, thus allowing a much more favorable view to be taken of the future of the field. Following the survey, private enterprise in the field on a large scale has already been stimulated. This has taken the form of further geophysical, geological, and mining, examinations. During 1937, further magnetic anomalies have been discovered. An additional two diamond drill holes have been put down. Each penetrated an ironstone ore body, as indicated by the Magnetic Survey, the core from one of them yielding assays exceeding one ounce of gold per ton.

### THE PORTLAND ROADS DISTRICT.

This field is situated in the recently-proclaimed Claudie River Gold Field, in Cape York Peninsula, Queensland, about Lat. 12° 30′ South. The nearest main centres of settlement are Cooktown, about 250 miles to the south, and Thursday Island, about 150 miles to the north.

The accompanying notes are a summary of an interim official geological report, in manuscript, by T. Rayner, official geologist.

According to Rayner, the predominant rock types encountered on a western traverse from the east coast of Queensland appear to be granite, "greenstone," and schist, presumably pre-Cambrian in age. These formations appear in reverse order on the continuation of the western traverse, indicating a "centre country" of schist, with outer links of granitic and "greenstone" rocks, the strike being, approximately, meridional.

The main Iron Range Field occurs in the "schists," and contains zones of hematite and magnetite-bearing rocks, known locally as "iron slates." Lesser fields, known as Packer's Creek and Scrubby Creek, occur in granite.

The Iron Range Field admits of a quadruple division, according to the nature of the ore deposits, namely:

1. The Iron Deposits.
2. The Gold-Iron Deposits.
3. The Southern Schist Zone.
4. The Northern Schist Zone.

Of these the iron deposits form a range of hills lying to the west of the known gold-bearing zone. They represent the replacement of slate beds. The iron "lode" was sampled at an outcrop where it appeared to be of considerable width. This appearance, however, was deceptive, owing to the natural and long-continued "shedding," during erosion, from the deposit on both sides of the resistant iron mass. Actually, at the place of sampling, the "lode" did not exceed 130 feet in width, the average assay value being recorded at 58.5 per cent iron approximately, and 13.5 per cent silica.

The gold-iron deposits lie easterly of the iron lodes, and are associated with beds of "iron-slate." The deposits are of two types; namely, rich, small "reefs" in schist, and wide, low-grade deposits of quartz in crushed "iron-slate." The "lodes" in this group have been formed at the intersection of "fractures." Intersections in schist have given rise to small rich deposits,

whereas intersections in "iron-slate" have yielded large low-grade ore bodies. The deposits, therefore, are "pipe"-like in form rather than tabular. The small rich deposits in the "schist" may be expected to pass into large low-grade bodies on intersecting "iron-slate" occurrences lower down.

The southern schist zone deposits are not associated with "iron-slate" beds, but conform, in places, with the planes of schistosity, whereas, in the types above mentioned, components exist both along, and transverse to, the direction of the schistosity.

The deposits in the northern schist zone consist of "crushed schist," containing lenses of ore, apparently of the pressure and replacement type, arranged in overlapping manner.

SYDNEY, AUSTRALIA,
*Dec. 6, 1937.*

# RECENTLY ADOPTED STANDARDS OF CLASSIFICATION OF COALS BY RANK AND BY GRADE.[1]

THOMAS A. HENDRICKS.[2]

ABSTRACT.

The purpose of this paper is to call attention to the classification of coals by rank and by grade which have been adopted as American standards by the American Society for Testing Materials and the American Standards Association. The two standard classifications are summarized, and the hope expressed that economic geologists engaged in coal studies will use these classifications in the future.

## INTRODUCTION.

THE classification of coals is of primary interest to economic geologists, and for that reason it seems desirable to bring to their attention the standard classifications of coals by rank and by grade which have been adopted by the American Society for Testing Materials and the American Standards Association.

In November, 1926, the American Engineering Standards Committee (now the American Standards Association) called a meeting of representatives of various professional societies and industrial, educational, and governmental organizations to consider what action should be taken on the classification of North American coals. This meeting was well attended and the group present was definitely in favor of attempting to prepare scientific and use classifications of all ranks of coal from lignite to anthracite. It was recommended that the work be done by a committee operating under the sponsorship of the American Society for Testing Materials and according to the rules of the American Standards Association.

[1] Published by permission of the Director, Geological Survey, United States Department of the Interior.

Presented before Society of Economic Geologists, Washington Meeting, Dec. 29, 1937.

[2] Geological Survey representative on the Sectional Committee on Coal Classification of the American Society for Testing Materials.

The Sectional Committee on Coal Classification of the American Society for Testing Materials met for the first time in June 1927. Mr. A. C. Fieldner, who represented the sponsoring society, was elected chairman and has served diligently and continuously in that capacity. The total membership of 29 individuals comprising the committee consisted of 8 producers, 2 distributors, 8 consumers, and 11 members representing general and scientific interests. Most of the members were acting in the capacity of representatives for large organizations that have a definite interest in coal. The personnel of the committee has changed somewhat throughout the decade of its activity, but the balance of interests represented has remained essentially unchanged.

The primary aim of the committee was to prepare standard classifications of coal by rank, type, and grade, and to establish standard practices for use in sampling, analyzing, and testing inherent characteristics of coal other than those of composition.

The greater part of that aim has been realized. Standards have been adopted for sampling and methods of analysis; and a tentative standard has been adopted for determining the agglomerating index or caking tendency of coals.[3] A modification of the United States Bureau of Mines' method is used for determining the weathering or slaking of coals pending the adoption of a method by the American Society for Testing Materials.[3] In addition, standard classifications of coal by rank and by grade have been prepared by the committee and have been adopted by both the American Society for Testing Materials and the American Standards Association.[3] No classification of coals by type has been prepared, as the subcommittee charged with the preparation of such a classification has concluded that the existing data are inadequate for the rigid demarcation of the various types of coal.

## CLASSIFICATION OF COALS BY RANK.

The A. S. T. M. classification of coals by rank is based on the degree of metamorphism, or progressive alteration, of coals in the natural series from lignite to anthracite. The basic scheme

[3] Full information regarding these standards may be obtained from the American Society for Testing Materials, 260 South Broad St., Philadelphia, Pa.

TABLE I.

CLASSIFICATION OF COALS BY RANK.[a]
F.C. = Fixed Carbon. V.M. = Volatile Matter.

| Class. | Group. | Limits of Fixed Carbon or B.t.u. Mineral-Matter-Free Basis. | Requisite Physical Properties. |
|---|---|---|---|
| I. Anthracitic | 1. Meta-anthracite. | Dry F.C., 98 per cent or more (Dry V.M., 2 per cent or less). | |
| | 2. Anthracite. | Dry F.C., 92 per cent or more and less than 98 per cent. (Dry V.M., 8 per cent or less and more than 2 per cent). | |
| | 3. Semianthracite. | Dry F.C., 86 per cent or more and less than 92 per cent (Dry V.M., 14 per cent or less and more than 8 per cent). | Non-agglomerating.[b] |
| II. Bituminous[d] | 1. Low volatile bituminous coal. | Dry F.C., 78 per cent or more and less than 86 per cent (Dry V.M., 22 per cent or less and more than 14 per cent). | |
| | 2. Medium volatile bituminous coal. | Dry F.C., 69 per cent or more and less than 78 per cent (Dry V.M., 31 per cent or less and more than 22 per cent). | |
| | 3. High volatile A bituminous coal. | Dry F.C., less than 69 per cent (Dry V.M., more than 31 per cent); and moist[c] B.t.u., 14,000[e] or more. | |
| | 4. High volatile B bituminous coal. | Moist[c] B.t.u., 13,000 or more and less than 14,000.[e] | |
| | 5. High volatile C bituminous coal. | Moist B.t.u., 11,000 or more and less than 13,000.[e] | Either agglomerating or non-weathering.[f] |
| III. Subbituminous | 1. Subbituminous A coal. | Moist B.t.u., 11,000 or more and less than 13,000.[e] | Both weathering and non-agglomerating. |
| | 2. Subbituminous B coal. | Moist B.t.u., 9,500 or more and less than 11,000.[e] | |
| | 3. Subbituminous C coal. | Moist B.t.u., 8,300 or more and less than 9,500.[e] | |
| IV. Lignitic | 1. Lignite. | Moist B.t.u., less than 8,300. | Consolidated. |
| | 2. Brown coal. | Moist B.t.u., less than 8,300. | Unconsolidated. |

*Footnotes on page 139.*

of classification is according to fixed carbon and calorific value (expressed in B.t.u.) calculated to the mineral-matter-free basis. The higher-rank coals are classified according to fixed carbon on the dry basis; and the lower-rank coals according to B.t.u. on the moist basis. Agglomerating and weathering indices are used to differentiate between certain adjacent groups. The designations of individual coals by this system differs only in a few border-line cases from their designations by the fuel ratio system developed by the Geological Survey, United States Department of the Interior, from the original fuel ratio system proposed by Persifor Frazer, Jr., in 1879. Such differences as do exist are the result of scientifically sound refinements of the earlier system.

Coals are classified by rank in accordance with Table I. It will be seen in Table I that

> Coals having calorific values of 14,000 B.t.u. or more on the moist, mineral-matter-free basis, and coals having fixed carbon of 69 percent or more on the dry, mineral-matter-free basis shall be classified according to fixed carbon on the dry, mineral-matter-free basis; coals having calorific values less than 14,000 B.t.u. on the moist, mineral-matter-free basis shall be classified according to B.t.u. on the moist, mineral-matter-free basis, provided the fixed carbon on the dry, mineral-matter-free basis is less than 69 percent.[4]

Coals showing weathering indices of less than 5 percent are considered non-weathering, and coals showing average weathering indices of 5 percent or more are considered weathering from the standpoint of classification.[5]

[4] Report of sectional committee on classification of coals, American Society of Testing Materials, preprint, p. 19, 1934.

[5] Idem, p. 23.

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[a] This classification does not include a few coals that have unusual physical and chemical properties and that come within the limits of fixed carbon or B.t.u. of the high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48 per cent dry, mineral-matter-free fixed carbon or have more than 15,500 moist mineral-matter-free B.t.u.

[b] If agglomerating, classify in low volatile group of bituminous class.

[c] Moist B.t.u. refers to coal containing its natural bed moisture but not including visible water on the surface of the coal.

[d] Pending the report of the Subcommittee on Origin and Composition and Methods of Analysis, it is recognized that there may be non-caking varieties in each group of bituminous coal.

[e] Coals having 69 per cent or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of B.t.u.

[f] There are three varieties of coal in the High-volatile C bituminous coal group, namely, Variety 1, agglomerating and non-weathering; Variety 2, agglomerating and weathering; Variety 3, non-agglomerating and non-weathering.

Coals having average agglomerating indices of 500 grams or more at a ratio of 15 parts sand to 1 part coal are considered agglomerating from the standpoint of classification.[6]

The classification of a coal bed, or a part of a coal bed, in any locality is based on the average analysis and calorific value (and agglomerating and weathering index where required) of not less than three and preferably five or more face samples taken in different and uniformly distributed localities, either within the same mine or closely adjacent mines representing a continuous and compact area not greater than approximately four square miles in regions of geological uniformity. In regions where conditions indicate that the coal probably varies rapidly in short distances the spacing of samples and grouping of analyses to provide average values shall not be such that coals of obviously different rank will be used in calculating average values.

Samples must be taken in accordance with the standard Bureau of Mines method or its equivalent, and must be placed in moisture-tight containers in the mine. Analyses of samples from outcrops or from weathered or oxidized coals are not acceptable for classification purposes.

A standard analytical method has been adopted and analyses used for classification purposes must be run by that method.[7] Special technique is required for samples containing more or less moisture than is natural for the bed and for samples containing more than 1.0 per cent of carbon dioxide occurring as carbonates.

## CLASSIFICATION OF COALS BY GRADE.

The specifications for classification of coals by grade serve as an index to the quality of the coals, as determined by calorific value, ash, and sulphur content, and ash-softening temperature.

Analyses are expressed on the basis of the coal as sampled. The calorific value of a coal is expressed in hundreds of B.t.u. to the nearest hundred, and ash, softening temperature of ash, and

[6] Gilmore, R. E., Connell, G. P., Nicolls, J. H. H.: Agglomerating and agglutinating tests for classifying weakly caking coals. A. I. M. E., Trans., Coal division, vol. 108, p. 255, 1934.

[7] 1933 Book of A. S. T. M. Standards, Part II, p. 269.

TABLE II.

SYMBOLS FOR GRADING COAL ACCORDING TO ASH, SOFTENING TEMPERATURE OF ASH, AND SULFUR.

(Analyses expressed on the basis of the coal as sampled.)

| Ash.[a] | | Softening Temperature of Ash.[b] | | Sulfur.[a] | |
|---|---|---|---|---|---|
| Symbol. | Per cent, Inclusive. | Symbol. | Degree Fahr., Inclusive. | Symbol. | Per cent, Inclusive. |
| A 4 | 0.0 to 4.0 | F 28 | 2800 and higher | S 0.7 | 0.0 to 0.7 |
| A 6 | 4.1 to 6.0 | F 26 | 2600 to 2790 | S 1.0 | 0.8 to 1.0 |
| A 8 | 6.1 to 8.0 | F 24 | 2400 to 2590 | S 1.3 | 1.1 to 1.3 |
| A 10 | 8.1 to 10.0 | F 22 | 2200 to 2390 | S 1.6 | 1.4 to 1.6 |
| A 12 | 10.1 to 12.0 | F 20 | 2000 to 2190 | S 2.0 | 1.7 to 2.0 |
| A 14 | 12.1 to 14.0 | F 20 minus | Less than 2000 | S 3.0 | 2.1 to 3.0 |
| A 16 | 14.1 to 16.0 | | | S 5.0 | 3.1 to 5.0 |
| A 18 | 16.1 to 18.0 | | | S 5.0 plus | 5.1 and higher |
| A 20 | 18.1 to 20.0 | | | | |
| A 20 plus | 20.1 and higher | | | | |

[a] Ash and sulphur shall be reported to the nearest 0.1 per cent by dropping the second decimal figure when it is 0.01 to 0.04 inclusive, and by increasing the percentage by 0.1 per cent when the second decimal figure is 0.05 to 0.09, inclusive. For example, 4.85 to 4.94 per cent, inclusive, shall be considered to be 4.9 per cent.

[b] Ash-softening temperatures shall be reported to the nearest 10° F. For example, 2635° to 2644° F., inclusive, shall be considered to be 2640° F.

sulphur content are expressed by symbols in accordance with Table II. For example, a coal designated as 132–A8–F24–S1.6, indicates a heating value of approximately 13,200 B.t.u., an ash content of 6.1 to 8.0 per cent, inclusive, an ash-softening temperature of 2400° to 2590° F., inclusive, and a sulphur content of 1.4 to 1.6 per cent, inclusive.

For purposes of classification by grade, coals are sampled to represent their condition as sold and in accordance with the standard method of sampling coal of the American Society for Testing Materials. They are likewise analyzed according to standard procedure.

## CONCLUSION.

In conclusion, it may be stated that the classification of coals by grade, as approved by the American Society for Testing Materials and American Standards Association, is based essentially on a compact formula that expresses four of the characteristics of the coal that are of primary importance in its utilization.

The classification of coals by rank is a refined and rigid division of coals into a series of groups that are arranged in order in accordance with the degree of alteration of the coals in the natural sequence from lignite to anthracite. The designation of any individual coal in this standard system would differ in only a few borderline cases from the designation in the system of classification by fuel ratios that has long been used by the Geological Survey and the Bureau of Mines, United States Department of the Interior. Such differences as do exist are the result of scientifically sound refinements of the earlier system.

These classifications represent the results of ten years of intensive work by individuals and organizations representing all fields of interest in coal. They are based on sound principles throughout, and it is to be hoped that they will be used by all individuals and groups in disposing of problems of rank and grade classification of coals.

U. S. Geological Survey,
Washington, D. C.,
*January 11, 1938.*

# SULPHIDE SILVER MINERALS—A CONTRIBUTION TO THEIR PYROSYNTHESIS AND TO THEIR IDENTIFICATION BY SELECTIVE IRIDESCENT FILMING.

A. M. GAUDIN AND D. W. McGLASHAN.

ABSTRACT.

Sulpho-salts of silver have been synthesized by melting together silver, arsenic, antimony, bismuth, copper, and lead with sulphur in iron bombs.

The phases obtained have been differentiated by selective iridescent filming. Corrections are proposed for the composition of some of the compounds.

Correlation between the filming behavior of synthetic preparations and natural minerals has been made as far as possible.

A key for the determination of sulpho-salts of silver is presented.

Preliminary explorations were made of the phase diagrams for several pseudo-binary and pseudo-ternary systems.

THE economic worth of many ores is dependent in large measure upon their silver content. Silver minerals occur in these ores generally as minute grains or veinlets, the determination of which has been uncertain by the usual mineralogical methods. Even if these minerals were in large grains their identification would be difficult, as they lack distinctive characteristics.

Accordingly, the general technique of selective iridescent filming [1]† was extended to the silver minerals. As a part of the development of this technique, it was found two years ago by W. R. Swiler,[2] that silver minerals do not respond to the filming solutions utilized by him. This paper presents results obtained with a new filming solution that permits clear-cut differentiation between sulphide silver minerals. It was soon realized that it is not possible to secure natural minerals pure enough to play the part of reference minerals. This in turn led to the synthesis of silver minerals and to the set-up of these synthetic minerals as standards. Although the synthesis of silver

† Super numbers, *i.e.* [1b] refer to bibliography at end of paper.

minerals is a necessity, if any progress is to be made in the general problem of identification of sulphide silver minerals, this synthesis must not be regarded only as a means to an end. It constitutes in itself a major scientific problem in the fields of chemistry and metallurgy. The present contribution, therefore, is both in the field of determinative mineralogy and in that of study of polyphase chemical systems.

Besides the two forms of silver sulphide (argentite and acanthite), silver occurs commonly as complex sulphides with elements in Group V of the periodic table, specifically arsenic, antimony and bismuth. It also occurs as complex sulphides with tin. There probably are also other compounds of silver with other metals and sulphur or with the same elements, selenium and tellurium. In addition, silver occurs in solid solution in a number of sulphide minerals either in substitution for other metals or perhaps even as an interstitial additive element.

This contribution does not deal directly with the synthesis or study of sulphide minerals containing silver in solid solution as a minor impurity. It deals in some detail, however, with the so-called sulpho-salts formed by silver with arsenic and sulphur; with antimony and sulphur; with bismuth and sulphur; with copper and sulphur; with copper, antimony and sulphur; and with copper, arsenic and sulphur. This study, however, is by no means exhaustive; many years of intensive work would be required to that end.

## FILMING TECHNIQUE.

The use of selective thin filming for identification evolved from the difficulties of other workers at Montana School of Mines to differentiate between briquetted particles of sulphide minerals. H. B. Henderson * working with tennantite-tetrahedrite was able to differentiate between these two minerals by use of a filming solution,[1b] and Gaudin and Malozemoff [1c] in working with pyrrhotite-pentlandite-chalcopyrite ore from the Falconbridge mine, Sudbury, Ontario, were able to differentiate between grains of

* At the time Mr. Henderson was associated with the senior writer of this paper as Cornelius F. Kelley Fellow in Mineral Dressing.

pentlandite and pyrrhotite in briquettes of flotation concentrate. The grains were so fine that the slight natural color distinction between pentlandite and pyrrhotite was insufficient for identification. After filming, pentlandite became sky-blue and pyrrhotite maroon so that even eutectic-like intergrowths of extreme intimacy could be resolved instantly and unequivocally. The possibilities of identification and differentiation by selective thin filming were realized and its value in industrial research as well as in science was established.

The method of selective iridescent filming consists in creating on the surface of minerals transparent films of such thickness that light interference takes place between beams reflected from the top and from the bottom of the film; the selective character of this filming arises from the fact that films of different thicknesses and different optical properties are formed on different minerals, thus giving different colors.[1d, 3a]

Aside from the composition of the filming medium, two other important factors affect the color obtained, namely the length of the filming time, which should be controlled by a stop-watch, and temperature of reaction.

The color obtained on the same mineral is not always exactly the same; this happens if the mineral is chemically anisotropic because the film thickness is not the same on crystals cut in different orientations.[3b] In addition, minor differences in color may occur because of local differences in stirring of the bath or because of other details such as macro-structure of the specimen. Differentiation by selective iridescent filming does not have to depend on minor color differences; it depends on sharply contrasting colors, each perhaps of several shades, obtained by filming for a precisely controlled length of time at a definite temperature.

In its application, the method of iridescent filming has consisted so far in oxidizing the surfaces of the minerals by immersion in a liquid bath. This particular way of applying the method has been followed in this work.

In developing solutions for the filming of silver minerals an oxidizing bath was sought that would yield an insoluble trans-

parent oxidation product. Iodine baths were chosen because it was believed they would meet these requirements. Various baths were tried by cut-and-try until a satisfactory solution was obtained. Later it was discovered that metallic silver had already been filmed iridescently with iodine by Evans in England [4] and by Tammann in Germany [5] and their co-workers.

In the preparation of filming solutions, different percentages of iodine were dissolved in methyl alcohol. Then acids were added in different proportions to the iodine-methyl alcohol solution until a bath was obtained that produced suitable colors on natural silver minerals. The solution was chosen that gave the greatest spread in differentiation between these minerals while producing consistent colors. Attention is called here to the fact that the filming bath finally selected is a non-aqueous solution. This shows that a wider field of solutions is available to choose from than was believed at first.

*Standard Silver Filming Solution.*—This solution is composed of one part 2 per cent iodine-methyl alcohol solution and one part of concentrated sulphuric acid by volume. To prepare this solution, the correct amount of iodine is first taken into methyl alcohol, to which an equal amount of concentrated sulphuric acid is slowly added, mixed, and cooled. Usually a loss in volume occurs on addition of the acid which must be corrected by adding methyl alcohol. The final solution contains iodine precipitate. Before immersing a specimen, the iodine should be allowed to settle. This usually takes a minute or two. The solution changes rapidly on exposure to air, possibly because of selective evaporation of the alcohol or of condensation of moisture, so the stock solution should be well stoppered and the bath should be kept covered. The bath has given satisfactory results at room temperature for an hour. The interference colors show a tendency to fade if a weathered solution is used. The solution described above is hereafter called the standard filming solution.

In using the solution, contamination of mineral surfaces by grease and oils must be avoided. If present, they may be removed by immersing the specimen in methyl alcohol or in acetone and washing in water.

The specimen to be filmed can be held with a pair of tongs, polished surface downward in the solution for short time periods; for long periods it can be placed, polished surface upward in the bottom of the vessel. On removing the specimen from the bath the polished surface must be washed *thoroughly and immediately* by a spray of methyl alcohol to remove the filming solution. The alcohol is removed by washing with a spray of acetone. The acetone evaporates rapidly leaving the polished surface clean and dry. The specimen is now ready for mounting and study. The film may be removed by buffing. Generally speaking, the films are very durable, at least in comparison with films obtained with other filming solutions on other minerals. Examples are known of films that retained differentiation value for over a year.

*Other Filming Solutions.*—Some experimental work was done with solutions of iodine in other alcohols than methanol. A 2 per cent solution of iodine in ethyl alcohol mixed with concentrated sulphuric acid was prepared in the same proportions as the standard filming solution. This solution differentiated between silver minerals fairly well. However, the colors were not as good as those developed by the standard solution. Furthermore, considerable difficulty was experienced in removing the solution from the surface of the specimen because of its viscosity.

Solutions made up with the same constituents as the standard silver filming solution but in different proportions did not differentiate as well as the standard solution. Of these solutions, those that had a lower proportion of sulphuric acid than the standard solution produced interference colors too rapidly, and non-uniformly.

Solutions of iodine in methanol with hydrochloric acid were also investigated. Broadly speaking they film too fast, so that control of the time of filming is impractical. But they probably will be useful for slow-filming compounds. Further work is in progress.

*The Standard Chromium Tri-Oxide-Hydrochloric Acid Filming Solution.*—The standard chromium tri-oxide-hydrochloric acid solution was used in some instances in this work. The preparation and use of this solution have been described.[1a]

## METHODS OF SYNTHESIS.

Pyrosynthesis of the sulphide silver minerals was chosen in preference to hydrosynthesis because of apparently lesser complexity and relatively high speed of preparation.

For synthesizing, a porcelain parting cup was fitted in a 1½" black iron pipe plug and sealed by a pipe cap. This constituted a simple bomb. The sealed bombs containing the mixtures were placed in a hot muffle furnace and were heated at the desired temperature for the time deemed necessary for the fusion. The charges were cooled in various ways, as recorded. A chromel-alumel thermocouple was used to measure the temperature.

Maximum temperatures ranged from 450° to 800° C. At 723° ± 2° C. iron undergoes a transition [6] and does not appear able to withstand the pressure created by the sulphur vapor. Experiments involving heating above this critical temperature were characterized by an extremely high mortality, but they were sometimes necessary.

At the desired temperature, the bombs were removed from the furnace and quenched in a stream of water; the bombs were opened usually without difficulty and the specimens were polished for microscope study.

## SILVER SULPHIDE-ARSENIC SULPHIDE SYSTEM.

In the chemical literature, the silver sulphide-arsenic sulphide system is treated as a binary system. It should more properly be regarded as a pseudo-binary system inasmuch as several arsenic sulphides are known.

According to Jaeger and van Klooster [7] two compounds are formed between silver sulphide and arsenic tri-sulphide; they show that the system really resolves itself into three sub-systems, each consisting of two phases miscible in the liquid state, and immiscible in the solid state. The general system features, therefore, three eutectics.

That silver sulphide occurs in two forms, one rhombic and one cubic, is well known and has been the object of recent measurements.[8] The transformation takes place at 175° C. Thus, ac-

cording to chemists, there should be four compounds in addition to arsenic sulphides.

Mineralogists [9-11] on the other hand recognize at least seven minerals; namely argentite and acanthite which correspond to the two forms of chemically-prepared silver sulphide; proustite and xanthoconite which have the same formula, $3Ag_2SAs_2S_3$, but different crystal form; smithite and trechmanite which also have the same formula, $Ag_2SAs_2S_3$, but different crystal form; and pearceite. The evidence for existence of xanthoconite and trechmanite leaves much to be desired. Assuming the descriptions of these minerals to be invalid and mere repetition of proustite and smithite, respectively, still leaves one important discrepancy between the chemical and mineralogical record, namely the existence or non-existence of pearceite.

A re-investigation of the chemical system was undertaken by melting together silver sulphide,* arsenic and sulphur.

Many specimens were synthesized and studied with the microscope. For the sake of brevity, only the most characteristic results are presented here (Tables I and II). A more complete record is available in a manuscript by one of us.[12]

Tables I and II record the proportions of constituents that were mixed together, the phases observed in each specimen, the structural relationship of the phases, the heat treatment, and the illustrative photomicrographs.

Attention is called to the fact that the composition of the finished specimens is not given. This is important in specimens containing a relatively large proportion of arsenic, inasmuch as arsenic and sulphur are both volatile and both capable of combining with the iron of the bomb. Although no attention was paid to the possible formation of arsenopyrite, the linings of some of the bombs suggested the presence of this mineral instead of the usual pyrite and pyrrhotite. It can, therefore, be concluded that the actual arsenic content of the specimens may well have been low in relation to the amount of arsenic put in,

* The silver sulphide was graciously prepared and donated by the Consolidated Mining and Smelting Company of Canada, Ltd., Trail, B. C., through the courtesy of R. W. Diamond, General Superintendent.

at least in specimens of high arsenic content, and possibly in all. It is not believed that the same difficulty occurred in the case of specimens made to contain elements other than arsenic.

TABLE I.

SELECTED DESCRIPTIVE LIST OF SPECIMENS PREPARED IN THE SILVER SULPHIDE-ARSENIC SULPHIDE SYSTEM, IN THE PRESENCE OF EXCESS SULPHUR.

| Weight in Grams | | Atomic Per Cent* | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|---|
| $Ag_2S$ | $As_2S_3$ | Ag | As | | | | |
| 4.51 | 0.91 | 83.2 | 16.8 | Argentite<br>Phase A<br>Sulphur | Rounded argentite dendrites in groundmass of Phase A | *a* | |
| 9.01 | 0.99 | 90.0 | 10.0 | Argentite<br>Phase A<br>Proustite<br>Smithite<br>Sulphur | Rounded argentite dendrites; interstitial proustite with inclusions of smithite; groundmass phase A | *b* | 5 |
| 8.02 | 1.98 | 80.1 | 19.9 | Phase A<br>Proustite<br>Smithite<br>Sulphur | Regular dendrites Phase A; surrounded by proustite; eutectic of proustite and smithite | *b* | 6 |
| 7.02 | 2.98 | 70.0 | 30.0 | Proustite<br>Smithite<br>Sulphur | Eutectic of proustite and smithite | *b* | 7 and 8 |
| 6.01 | 3.99 | 59.6 | 40.4 | Proustite<br>Smithite<br>Sulphur | Eutectic of proustite and smithite; smithite inclusions | *b* | |
| 5.02 | 4.99 | 49.5 | 50.5 | Proustite<br>Smithite<br>Sulphur | Smithite bundles with interstitial proustite | *b* | |
| 4.02 | 5.98 | 40.0 | 60.0 | Proustite<br>Smithite<br>Sulphur | Smithite bundles with a little interstitial proustite | *b* | 9 |
| 3.06 | 6.94 | 30.9 | 69.7 | Proustite<br>Smithite<br>Sulphur | Smithite groundmass containing minute quantities of interstitial proustite | *b* | |
| 2.01 | 7.99 | 19.9 | 80.1 | Smithite<br>Glassy phase<br>Sulphur | Smithite—and glassy phase | *b* | |

*Heat Treatment:*

*a*. Heated to 540° C.; cooled slowly in furnace; quenched from 200°–250° C.

*b*. Heated to 550° C.; cooled slowly in furnace; quenched from 200° C.

* Of the metals only (disregarding sulphur).

TABLE II.

EFFECT OF PRESENCE OR ABSENCE OF EXCESS SULPHUR ON PHASE FORMATION AND STRUCTURE AT A COMPOSITION APPROXIMATING THAT OF PROUSTITE (HEATED TO 520° C., COOLED SLOWLY IN FURNACE OVER A PERIOD OF 14 HOURS; QUENCHED FROM 150° C.).

| Weight in Grams | | | Atomic Per Cent* | | Phases | Structure | Figure |
|---|---|---|---|---|---|---|---|
| $Ag_2S$ | $As_2S_3$ | Sulphur | Ag | As | | | |
| 9.02 | 3.02 | 1.20 | 74.8 | 25.2 | Silver<br>Argentite<br>Proustite | Silver idiomorphs associated with argentite; argentite dendrites in proustite. Ternary eutectic-like structure between silver, argentite and proustite | 10 |
| 9.02 | 3.02 | 1.50 | 74.8 | 25.2 | Silver<br>Argentite<br>Proustite | Ternary eutectic-like structure between silver, argentite and proustite, proustite being for the most abundant constituent | |
| 9.02 | 3.02 | 2.50 | 74.8 | 25.2 | Argentite<br>Proustite | Proustite forms groundmass with argentite interstitial | |
| 9.02 | 3.02 | 7.00 | 74.8 | 25.2 | Phase A<br>Proustite<br>Smithite<br>Sulphur | Large regular dendrites phase A surrounded by proustite; coarse eutectic of proustite with smithite | |

* Of the metals only (disregarding sulphur).

In Table I are presented the results obtained in the presence of excess sulphur. Table II shows the great influence of presence of excess sulphur or lack of sulphur, not only on structural relations, but on phase formation.

Table I shows that in addition to sulphur four phases are obtained. Arsenic sulphide might be expected but none was identified, although a glassy phase was occasionally seen among specimens very high in arsenic. Of the four silver-bearing phases three answer well to the descriptions of argentite, proustite, and smithite, respectively. The fourth, referred to in this report as phase A, was observed *only* in specimens made in the presence of excess sulphur, and it was *always* observed in specimens with excess sulphur if of the proper composition.

*Discussion of the Phases.*

Some difference in appearance of the phases was observed on unfilmed surfaces, partly by faint color differences and partly by behavior under polarized light. However, no real progress in structural analysis could be made without filming. Actual improvement in appearance by filming was in fact vastly more vivid than is portrayed by lifeless black-and-white photomicrographs (Figs. 7 and 8). So, the standard silver filming solution was used for differentiation and identification. The identification guide at the end of this paper (Table IX) correlates the colors obtained with duration of immersion.

*Argentite* filmed for twenty seconds exhibits characteristic first order bright blue to second order yellow interference colors. Large grains film slower in the core and faster at the rim, while fine grains generally film fast. This variation in color can be explained by the high relief of argentite against neighboring minerals. It is clear that as the specimen is viewed vertically under the microscope the thickness of the film on the edges of argentite grains is greater than the thickness on the core, since the film is traversed at an angle instead of normally. Hence, the edges appear to film faster. This characteristic is useful for the identification of argentite. It was verified on natural argentite from the Boundary Mine, B. C., donated by Mr. P. E. Crane, but it could not be verified on a sample of "argentite" purchased from a dealer and stated to have come from Freiberg, Germany. That sample was not argentite and probably not a silver mineral at all.

*Phase A* is definitely light tan-cream in color in contrast with either argentite or proustite. Its reflectivity when unfilmed is clearly less than that of either argentite or proustite. It appears to be isotropic. In polished unfilmed section, phase A and phase B look exactly like some large crystals of natural silver minerals from the Boundary Mine, B. C. These natural crystals are clearly not anisotropic megascopically but they fail to display anisotropy in polished section (possibly because aggregates of crystals were not available). By all usual identification criteria these natural crystals would, however, be determined as stephanite.

Phase A must be intermediate in composition between argentite and proustite; this is brought out by their structural relationships. It is isomorphous with phase B, discussed hereafter in connection with the system silver sulphide-antimony sulphide; in fact solid solutions of phases A and B have been prepared. Phase B contains about 9 mols of $Ag_2S$ for each mol of $Sb_2S_3$. It may, therefore, be inferred that phase A likewise contains about 9 mols of $Ag_2S$ for each mol of $As_2S_3$. Semi-quantitative estimates of the composition of phase A made from microscope counts of polished sections and on the basis of the proportions of silver and arsenic mixed in the charge agree with the conclusion that the atomic proportion of silver to arsenic is 9 to 1, but this evidence is not dependable because of the possibility of arsenic loss during heating.

The conclusion is that phase A is pearceite. This conclusion is offered in spite of the fact that pearceite is reported to be monoclinic [9-11] and that phase A appears to be isotropic.

A series of fusions having similar atomic proportions of silver and arsenic, but containing varying amounts of sulphur was prepared (Table II). It is obvious that all these specimens lost sulphur on melting, but their general relationship as to sulphur content is preserved. The specimen made with just enough sulphur to yield trivalent arsenic sulphide (Fig. 10) did not contain phase A. This specimen contained metallic silver, argentite and proustite. The intermediate specimens made with some excess sulphur show the same phases, but with more proustite and less metallic silver and argentite. The last specimen of this series prepared with a large excess of sulphur, contains phase A in large dendrites surrounded by typical proustite and a eutectic-like structure of proustite and smithite. Obviously no specimen showing native silver can have had an excess of sulphur when it froze (since silver sulphide at the temperatures involved has a negligible dissociation pressure). Thus, synthetic specimens lacking in an excess of sulphur do not contain phase A; those that do contain excess sulphur contain phase A. It is likely then, that phase A contains more sulphur than is indicated by a combination of silver

sulphide with arsenic tri-sulphide; in other words that the dissociation pressure of this compound of silver sulphide, arsenic tri-sulphide and sulphur at its freezing point, is lower than the vapor pressure of sulphur at that temperature. Could not phase A (pearceite) be regarded as a compound of silver sulphide with pentavalent arsenic sulphide, just as enargite may be regarded as a compound of cuprous sulphide with pentavalent arsenic sulphide?

Synthetic *proustite* formed in the presence of excess sulphur is analogous in all characteristics to the natural mineral. The same sequence of interference colors for various periods of immersion in the standard silver filming solution have been observed on natural proustite from several occurrences.

Proustite, if formed in the presence of metallic silver, films somewhat faster than normal proustite. This change in color is perhaps attributable to silver in solid solution in the proustite (or to a deficiency of sulphur). This variety of proustite is referred to as sulphur-poor proustite solid solution, although definite proof is lacking.

*Smithite.*—In spite of the unavailability of natural smithite there is no ground to doubt the identity of the synthetic and natural compounds; the characteristics recorded by mineralogists agree closely with those observed in the synthetic product. A much longer period of immersion in the standard filming solution is necessary to produce interference colors on this mineral than is necessary on other members of this system.

Since smithite and proustite are both anisotropic, both substantially bluish white in color by reflected light, both transparent and displaying internal reflections, there has been until now no way of ascertaining whether aggregates of arsenical ruby silver are wholly proustite or wholly smithite or a mechanical mixture of the two. This has, no doubt, led to the unwitting invention of rarities such as xanthoconite, rittingerite, trechmanite and others.

### *Discussion of the Structures.*

*Argentite* is always the first phase to crystallize. It forms rounded dendrites in rather regular patterns. It is also found in

eutectic-like structure * with proustite (in the absence of excess sulphur) but not with any other phase.

*Phase A* occurs in dendrites with rectilinear outlines if the amount of silver is insufficient for the production of any argentite. It also surrounds argentite dendrites wherever it occurs with argentite. Phase A has not been observed in eutectic-like structures with proustite.

*Proustite* occurs as thin envelopes around phase A, in magnificent eutectic relationships with smithite, and (in specimens lacking excess sulphur) in triple eutectic-like structure with metallic silver and argentite.

*Smithite* occurs in eutectic structures with proustite and in sheaf-like growths of crystals with interstitial proustite.

*Metallic silver* has been observed to occur as idiomorphic crystals and in eutectic-like association with argentite and proustite in specimens deficient in sulphur.

## *Conclusion.*

Since so much depends upon whether sulphur is present in excess or not, it is desirable to consider two cases corresponding, one to deficiency in sulphur and the other to excess sulphur.

If no excess sulphur is present, the equilibrium diagram proposed by Jaeger and van Klooster [7] is probably correct. However, to prepare specimens which show neither an excess nor a deficiency of sulphur with the apparatus available is difficult of achievement.

If excess sulphur is present conditions are probably somewhat as represented in Fig. 1. This diagram is presented merely as a tentative iconograph of the experimental data. It is not an equilibrium diagram for several reasons: (*a*) equilibria were not

* An attempt is made in this paper to use the expression "eutectic structure" whenever it is reasonably certain that the structure resulted from freezing at constant temperature. The term "eutectic-like structure" is reserved for similar structures that have arisen under conditions of freezing through an appreciable range in temperature. Strictly speaking, eutectic structures occur only in binary systems and under special conditions in more complicated systems. Eutectic-like structures are the common occurrence in ternary and more complex systems.

sought or attained in the experiments, (*b*) no thermal data were secured, (*c*) the presence of excess sulphur makes three dimensions necessary to picture equilibrium conditions. Fig. 1, how-

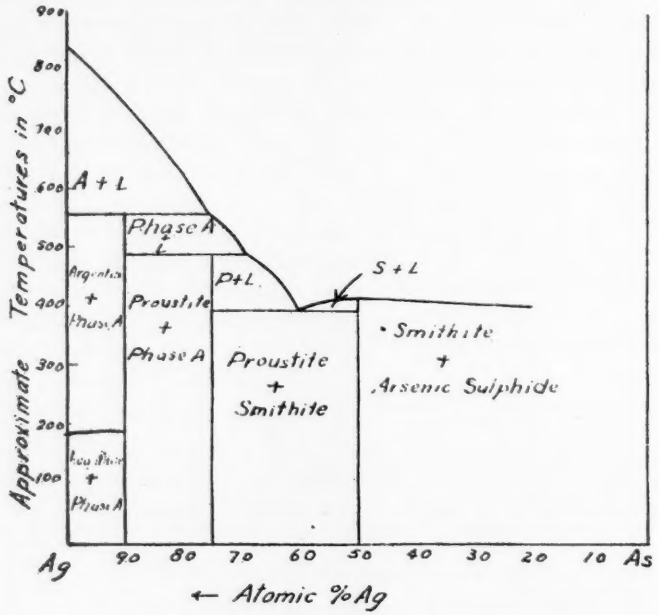


FIG. 1. Sketch of the silver sulphide-arsenic sulphide system (with excess sulphur).

ever, does present a basis for comparison with conditions obtained in the absence of excess sulphur.

### SILVER SULPHIDE-ANTIMONY SULPHIDE SYSTEM.

In chemical literature the system silver sulphide-antimony sulphide is treated as a binary. Antimony, like arsenic, may be either trivalent or pentavalent so that more than one sulphide of antimony could exist. The system silver sulphide-antimony sulphide is then truly a ternary system. Two compound sulphides

have been reported,[17, 18] namely, $3Ag_2S \cdot Sb_2S_3$ and $Ag_2S \cdot Sb_2S_3$. These compounds correspond respectively to the minerals pyrargyrite and miargyrite. In addition to argentite, acanthite, stibnite, pyrargyrite and miargyrite, mineralogists have described polyargyrite, polybasite, stephanite, pyrostilpnite and perhaps others. Of these, pyrostilpnite and polyargyrite are not widely accepted, if not indeed discredited. The discrepancy between chemically prepared compounds and minerals is thus limited to polybasite and stephanite.

Table III presents the most characteristic results that were obtained. It is similar to tables I and II.

TABLE III.

SELECTED DESCRIPTIVE LIST OF SPECIMENS PREPARED IN THE SILVER SULPHIDE-ANTIMONY SULPHIDE SYSTEM WITH EXCESS SULPHUR.

| Weight in Grams | | Atomic Per Cent | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|---|
| $Ag_2S$ | $Sb_2S_3$ | Ag | Sb | | | | |
| 5.21 | 0.57 | 92.8 | 7.2 | Argentite<br>Phase B<br>Pyrargyrite<br>Sulphur | Argentite dendrites surrounded by phase B; pyrargyrite interstitial | *a* | 11 |
| 9.00 | 1.00 | 92.5 | 7.5 | Argentite<br>Phase B<br>Pyrargyrite<br>Sulphur | Abundant dendrites of argentite surrounded by phase B, and by a eutectic-like structure of much pyrargyrite and a little argentite | *b* | 12 |
| 6.95 | 1.05 | 90.1 | 9.9 | Argentite<br>Phase B<br>Pyrargyrite<br>Sulphur | Rounded dendrites of argentite; eutectic-like structure of phase B and pyrargyrite | *b* | 13 and 14 |
| 8.00 | 2.00 | 84.7 | 15.3 | Phase B<br>Pyrargyrite<br>Argentite<br>Sulphur | Irregular dendrites phase B; eutectic-like structure of argentite with pyrargyrite | *c* | |
| 8.00 | 4.00 | 73.3 | 26.7 | Argentite<br>Phase B<br>Pyrargyrite<br>Sulphur | Argentite dendrites or inclusions in phase B. Phase B as irregular dendrites and eutectic-like structure with pyrargyrite | *c* | |
| 6.00 | 4.00 | 67.3 | 32.7 | Pyrargyrite<br>Miargyrite<br>Sulphur | Dendrites of miargyrite in eutectic of miargyrite and pyrargyrite. Pyrargyrite is the most abundant constituent | *d* | |

TABLE III (*Continued*).

| Weight in Grams | | Atomic Per Cent | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|---|
| $Ag_2S$ | $Sb_2S_3$ | Ag | Sb | | | | |
| 5.50 | 4.50 | 62.7 | 37.3 | Pyrargyrite<br>Miargyrite<br>Sulphur | Increasing amount of miargyrite dendrites in eutectic of pyrargyrite and miargyrite. Pyrargyrite is the most abundant constituent | *d* | |
| 5.00 | 5.00 | 57.8 | 42.2 | Pyrargyrite<br>Miargyrite<br>Sulphur | Dendrites of miargyrite in eutectic of pyrargyrite and miargyrite. Miargyrite is the most abundant constituent | *d* | 15 |
| 4.00 | 6.00 | 47.8 | 52.2 | Miargyrite<br>Stibnite<br>Sulphur | Small irregular inclusions of stibnite in groundmass of miargyrite | *d* | |
| 3.00 | 7.00 | 37.0 | 63.0 | Miargyrite<br>Stibnite<br>Sulphur | Dendrites of miargyrite in eutectic of stibnite and miargyrite | *d* | 16 |

*Heat Treatments:*

*a*. Heated to 540° C. and cooled slowly by sealing furnace door. Quenched from 200–250° C.

*b*. Heated to 625–640° C. and cooled slowly for 5 hours. Quenched from 350–375° C.

*c*. Heated to 650° and cooled slowly by sealing furnace door. Quenched from 350°–375° C.

*d*. Heated to 560° C. and cooled slowly in furnace. Quenched from 200° C.

Table III shows that besides sulphur, five phases are formed. Of the five phases, four answer to the description of argentite, pyrargyrite, miargyrite and stibnite. The fifth, referred to as phase B, was observed *only* in specimens made in the presence of excess sulphur, and it was *always* observed in specimens with excess sulphur, if of the proper composition. Phase B in every respect is the counterpart of phase A, observed in the silver sulphide-arsenic sulphide system, with which it is isomorphous.

### *Discussion of Phases.*

*Argentite* immersed for 20 seconds in the standard silver-filming solution yielded characteristic first order bright blue to second order yellow interference colors. This behavior has already been discussed.

*Phase B* is characterized by an extremely smooth polish, pale tan-cream color (when unfilmed) against argentite or pyrargyrite. It appears isotropic.

Several volume estimations were made of the relative amounts of phase B and associated phases. Some variation was observed, but as a whole the estimations indicate that silver and antimony in phase B are in atomic ratio of about 9 to 1. This is shown by Table IV. Thus, the formula for phase B may well be $9Ag_2S \cdot Sb_2S_3$ or $9Ag_2S \cdot Sb_2S_5$. As has already been indicated, phase B is not formed unless excess sulphur is present. Formula $9Ag_2S \cdot Sb_2S_5$ is, therefore, more likely. No natural mineral is regarded to have such a formula, but phase B may profitably be compared with both stephanite and polybasite.

TABLE IV.

COMPOSITION OF PHASE B.

| Specimen Number | Atomic Per Cent of Antimony | Volume Per Cent of Phases | | | Calculated Atomic Per Cent of Antimony in Phase B (in relation to antimony plus silver) |
|---|---|---|---|---|---|
| | | Argentite | B | Pyrargyrite | |
| 2B35 | 10.0 | 27 | 50 | 23 | 8.6 |
| 2B16 | 10.0 | 28 | 43 | 29 | 11.7 |
| | | | | | Average 10.2 |

Both polybasite and stephanite are reported to be anisotropic. Phase B, on the contrary, appears isotropic, although it is not impossible for it to be slightly anisotropic. The color of unfilmed phase B agrees well with that of unfilmed stephanite.* The color of unfilmed phase B also agrees with the color of an unfilmed specimen of polybasite likewise loaned by Dr. Hewett, and with that of several specimens donated by Mr. P. E. Crane from the Boundary Mine, B. C. This natural mineral occurs in large crystals and under the microscope it fails to appear anisotropic. It agrees completely in appearance with phase B both before and after filming. After filming, the U. S. Geological Survey stephanite agrees with phase B and is obviously a pure mineral, but the "polybasite" fails to agree with phase B. Furthermore,

* Kindly loaned by Dr. D. F. Hewett of the U. S. Geological Survey.

the U. S. Geological Survey "polybasite" is a complex mixture of substances so that its value as a reference specimen is doubtful. In view of the above evidence the writers feel that the agreement between phase B and stephanite is fair but not conclusive.

Synthetic *pyrargyrite* is analogous in all characteristics to the natural mineral. The same sequence of interference colors for various periods of immersion in the standard silver filming solution have been observed on natural pyrargyrite. Natural ruby silvers consisting of pyrargyrite and proustite were observed. By all customary microscope standards they could not be differentiated, but by filming no mistake is possible. The utility of selective iridescent filming as a tool in paragenetic study is obvious.

Synthetic *miargyrite* appears identical to the natural mineral. No natural miargyrite was available for comparison; but from the characteristics recorded by mineralogists, it may be concluded that the synthetic product is identical with the natural product. As in the case of smithite, a longer period of immersion is necessary to produce interference colors on miargyrite than on other sulpho-salts in the same system.

Synthetic *stibnite* is analogous to the natural mineral. In specimens containing stibnite the standard chromium trioxide-hydrochloric acid filming solution was used for differentiation and identification. By use of this solution, the same sequence of interference colors can be produced as on natural stibnite but they are formed somewhat slower. Stibnite synthesized in the absence of silver, however, films at the same rate as natural stibnite. This difference in behaviour suggests that the stibnite synthesized with silver contains perhaps a little silver in solid solution.

### *Discussion of the Structures.*

In general, the structures observed are simple.

*Argentite* is always the first phase to crystallize, forming rounded dendrites. It is also found in eutectic-like structure with pyrargyrite.

*Phase B* occurs as regular dendrites wherever the amount of

silver is insufficient for the production of argentite. It surrounds argentite dendrites wherever it occurs with argentite. Phase B is also found in eutectic-like structure with pyrargyrite but not with any other phase.

*Pyrargyrite* occurs as an interstitial constituent, in eutectic-like structure with argentite, in eutectic-like structure with phase B, and in eutectic structure with miargyrite. Where in eutectic-like structure with either argentite or phase B, it is the more abundant constituent.

*Miargyrite* occurs as dendrites, as eutectic with pyrargyrite, and as eutectic with stibnite.

*Stibnite* occurs as irregular dendrites in specimens containing much antimony sulphide. In others, it occurs as eutectic with miargyrite.

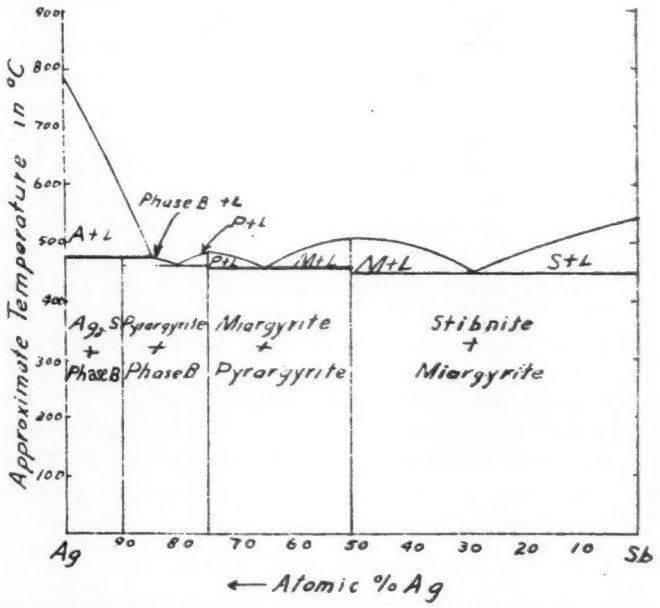


FIG. 2. Sketch of the silver sulphide-antimony sulphide system (with excess sulphur).

### *Conclusion.*

Since no eutectic was found to occur between phase B and argentite, an incongruent melting point is shown for phase B in Fig. 2. This figure is presented as a tentative iconograph of the experimental data; like Fig. 1 for the silver sulphide-antimony sulphide system, this diagram is not an equilibrium diagram.

## SILVER SULPHIDE-BISMUTH SULPHIDE SYSTEM.

There is no chemical literature concerning this system. Mineralogists list one mineral, matildite, $Ag_2S \cdot Bi_2S_3$, belonging in this system. Another mineral, tapalpite, is listed which may possibly belong in this system. Tapalpite, however, is generally formulated to contain tellurium in solid solution, replacing sulphur $(3Ag_2(Te, S) \cdot Bi_2(Te, S)$. Its properties, furthermore, are not definitely established.

In view of the lack of substantial information concerning the system $Ag_2S$–$Bi_2S_3$, an investigation was undertaken by melting together silver sulphide, powdered bismuth and sulphur. (Upon analysis the bismuth was found to contain no appreciable amount of impurities.) The results obtained are recorded in Table V.

Besides argentite and bismuthinite two phases were obtained. These phases seem to be matildite and a compound, probably $3Ag_2S \cdot Bi_2S_3$, which has been termed phase D.

The standard silver-filming solution was used for the differentiation and identification of argentite and of phase D. Since neither matildite nor bismuthinite can be filmed with the standard solutions, specially prepared iodine-methyl alcohol-hydrochloric acid solutions were used to film matildite and to differentiate it from other phases. Bismuthinite is not readily filmed by iodine solutions, but it has been filmed by solutions of a different composition developed by other investigators at Montana School of Mines.

### *Discussion of Phases.*

*Argentite,* in this system, has all the characteristics observed in previous systems.

TABLE V.

SELECTED DESCRIPTIVE LIST OF SPECIMENS PREPARED IN THE SILVER SULPHIDE-BISMUTH SULPHIDE SYSTEM MADE WITH EXCESS SULPHUR

| Weight in Grams | | Atomic Per Cent | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|---|
| $Ag_2S$ | $Bi_2S_3$ | Ag | Bi | | | | |
| 8.13 | 1.87 | 90.1 | 9.9 | Argentite<br>Phase D<br>Sulphur | Rounded dendrites of argentite in eutectic of argentite and phase D. Argentite is the more abundant constituent | *a* | 17 |
| 6.58 | 3.42 | 80.0 | 20.0 | Phase D<br>Argentite<br>Sulphur | Rounded dendrites of phase D in eutectic of phase D and argentite. Phase D is the more abundant constituent. Occasional dendrites of argentite. This indicates imperfect mixing of the charge | *a* | 18 |
| 5.92 | 4.08 | 75.3 | 24.7 | Phase D<br>Argentite<br>Sulphur | Large dendrites of phase D in eutectic of argentite and phase D. Phase D is by far the more abundant constituent | *a* | |
| 2.10 | 3.00 | 58.4 | 41.6 | Phase D<br>Matildite<br>Sulphur | Phase D in eutectic of matildite and phase D. Phase D is by far the more abundant constituent | *a* | 19 |
| 1.94 | 3.06 | 55.2 | 44.8 | Phase D<br>Argentite<br>Sulpnur | Phase D in eutectic of phase D and matildite. Phase D is the more abundant constituent | *a* | |
| 1.71 | 3.24 | 52.3 | 47.7 | Phase D<br>Matildite<br>Sulphur | Phase D in eutectic of phase D and matildite | | |
| 1.64 | 3.42 | 49.8 | 50.2 | Matildite<br>Bismuthinite<br>Phase D<br>Sulphur | Almost completely matildite. A few inclusions of bismuthinite and of phase D. | *a* | |
| 2.43 | 7.57 | 40.0 | 60.0 | Matildite<br>Bismuthinite<br>Sulphur | Matildite with included crystals of bismuthinite | *b* | |
| 1.70 | 8.30 | 29.8 | 70.2 | Matildite<br>Bismuthinite<br>Sulphur | Matildite with considerable included bismuthinite | *b* | 20 |
| 1.07 | 8.93 | 19.8 | 80.2 | Bismuthinite<br>Matildite<br>Sulphur | Bismuthinite crystals with interstitial matildite | *a* | |

*Heat Treatment:*

*a.* Heated to 675° C., cooled slowly in furnace to 300° and quenched.

*b.* Heated to 650° C.. cooled slowly in furnace to 100° and quenched.

*Phase D* is brilliant white against argentite in unfilmed polished sections. It is estimated that its reflectivity is appreciably higher than that of galena.

From its occurrence, and by volume estimations in various specimens containing it with argentite, it was concluded that phase D holds silver and bismuth in the atomic ratio of 3 to 1. The formula for phase D is then probably $3Ag_2S \cdot Bi_2S_3$. In this formula bismuth is regarded as trivalent since phase D forms either in the presence or in the absence of excess sulphur. The atomic proportions of silver and bismuth indicated from these observations correspond closely to the proportion of silver and bismuth in the mineral tapalpite.

Synthetic *matildite* appears analogous to the natural mineral. No natural matildite was available for comparison; but from the characteristics recorded, it can be concluded that the synthetic product is matildite.

Synthetic *bismuthinite* is identical in all characteristics with the natural mineral.

### *Discussion of the Structures.*

*Argentite* occurs in rounded dendrites and as a eutectic with phase D.

*Phase D* occurs as rounded and irregular dendrites and as a eutectic with argentite or with matildite. Some specimens are made up almost entirely of phase D.

*Matildite* occurs as a eutectic with phase D, as irregular dendrites, and as the groundmass when associated with bismuthinite.

*Bismuthinite* occurs in large crystals. Its failure to form a eutectic with matildite suggests that matildite has an incongruent melting point.

### *Conclusion.*

Although the specimens studied were not completely satisfactory, a eutectic was found between argentite and phase D and between phase D and matildite. Eutectic structures were not observed between matildite and bismuthinite. Fig. 3 presents

these conclusions in graphic form. This diagram is not an equilibrium diagram because of the lack of thermal data, but the writers believe it is generally representative of the facts. Attention is called to the fact that considerable solid solution of

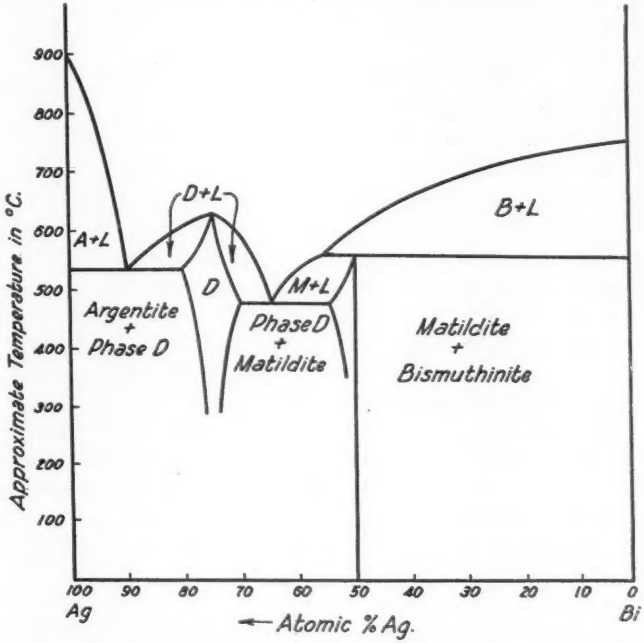


FIG. 3. Sketch of the silver sulphide-bismuth sulphide system (with excess sulphur).

excess silver sulphide or bismuth sulphide in phase D must be included in this diagram, in the light of Table V.

### LEAD SULPHIDE-SILVER SULPHIDE SYSTEM.

A series of specimens were prepared ranging from 80 to 20 atomic per cent lead. The results confirm in part the diagram as given in the chemical literature [14] in that there is no compound

formed between silver sulphide and lead sulphide and in that a simple eutectic of silver sulphide with lead sulphide is formed. There is no mention in the literature of solid solution, and the observations made with both standard filming solutions compel the conclusion that solid solution of lead sulphide in argentite and of silver sulphide in galena must occur.

### SILVER SULPHIDE-COPPER SULPHIDE SYSTEM.

Although this system was not investigated in detail some attempts were made at synthesizing stromeyerite by melting together silver sulphide and finely ground chalcocite. The results as a whole were disappointing, covellite always being obtained with argentite whenever slow cooling in the presence of excess sulphur was used and argentiferous chalcocite or cupriferous argentite whenever excess sulphur was not employed. It is believed that the temperatures of solidification are appreciably above the decomposition temperature of stromeyerite. Synthesis of stromeyerite from mixtures of powdered and compressed sulphides of copper and silver has recently been reported as occurring at moderate temperature.[15] It is obvious, therefore, that mixed crystals of chalcocite in argentite should yield stromeyerite upon annealing at the proper temperature: this method of synthesis would indeed be simpler and easier to effect than that of Schwartz since it does not require anything like the atomic migration in the solid state, which his method requires.

### SILVER SULPHIDE-ANTIMONY SULPHIDE-COPPER SULPHIDE.

No data are available in the chemical literature concerning this system. In this report this system is treated as a ternary system, although it is more complex.

Data are available for the pseudo-binaries that form the boundaries of the pseudo-ternary system. Two of the three pseudo-binaries have already been treated in this paper; namely, the cuprous sulphide-silver sulphide and the silver sulphide-antimony sulphide pseudo-binaries. For the pseudo-binary antimony sulphide-copper sulphide data are available for the condition of formation of compounds in the absence of excess sul-

phur.[16] This particular pseudo-binary obviously needs revision or at least extension to the condition of preparation in the presence of excess sulphur. The data now available in the literature show that two compounds are formed consisting respectively of three mols of cuprous sulphide and one mol of cuprous sulphide to one mol of antimony trisulphide.

No compounds containing copper sulphide, silver sulphide and antimony sulphide together have been synthesized.

In addition to the minerals in the silver sulphide-antimony sulphide binary which have already been discussed, mineralogists recognize:

(*a*) the sulphides of copper, covellite, CuS, and chalcocite, $Cu_2S$;
(*b*) a sulphide of copper and silver, stromeyerite, $Cu_2S \cdot Ag_2S$;
(*c*) three sulphides of copper and antimony, chalcostibite (wolfsbergite), $Cu_2S \cdot Sb_2S_3$, tetrahedrite, and famatinite, $3Cu_2S \cdot Sb_2S_5$;
(*d*) a compound of silver sulphide, copper sulphide and antimony sulphide, polybasite.

Tetrahedrite is generally reported as ranging from $3Cu_2S \cdot Sb_2S_3$ to $4Cu_2S \cdot Sb_2S_3$. The formula for polybasite is probably in need of reconsideration.

*The Phases.*

Fig. 4 presents among other things, the position in atomic percentage of the various phases that were observed in the present investigation (triangular dots). Accurate representation would require a tetrahedron. To avoid the difficulty of using a solid model, changes in amount of sulphur are regarded as changing the position of each phase at right angles to the paper. Thus covellite and chalcocite appear in the same position and likewise tetrahedrite and famatinite. Fig. 4 shows that twelve phases are involved in the present system of which ten are accepted mineralogically and chemically and two are discoveries of synthetic minerals made during the course of the present investigation. These two phases more or less fit the characteristics accepted for two silver minerals.

In presenting the actual experimental data (Table VI) specimens are considered first that contain the smallest amount of antimony. The first group contains only 5 at. per cent Sb; the next

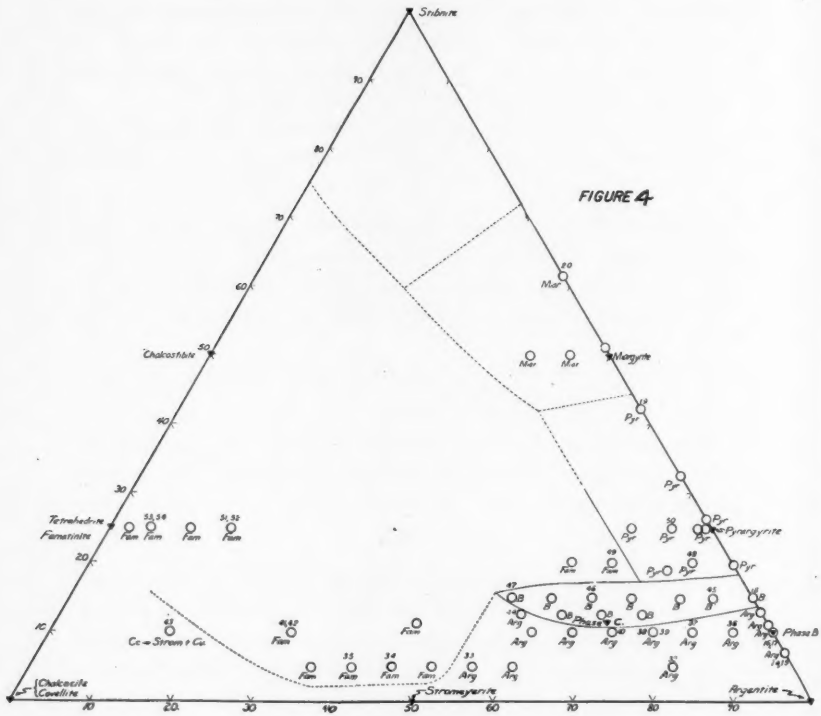


FIG. 4. Sketch of the silver sulphide-antimony sulphide-copper sulphide system (with excess sulphur).

group 10, the next group 12½, etc. Within the first group the first specimen considered is that containing the least amount of copper followed by specimens with increasing amounts of copper until exhaustion of the specimens containing 5 at. per cent Sb. The same sequence is followed for all of the specimens.

TABLE VI.

CHARACTERISTIC SPECIMENS PREPARED IN THE SILVER SULPHIDE-ANTIMONY SULPHIDE-COPPER SULPHIDE SYSTEM WITH EXCESS SULPHUR *

| Composition Atomic Per Cent | | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|
| Ag | Sb | Cu | | | | |
| 80.0 | 5.1 | 14.9 | Argentite<br>Phase B<br>Phase C<br>Famatinite<br>Covellite<br>Sulphur | Fairly coarse dendrites of argentite; interstitial matter in some areas is covellite plus eutectic-like argentite with famatinite; in others it is an intergrowth of phase B with phase C, with crystals of C pushing their way into the argentite. The specimen is not homogeneous | *a* | |
| 55.1 | 4.9 | 40.0 | Famatinite<br>Argentite<br>Covellite<br>Sulphur | Eutectic-like structure of argentite and famatinite; argentite more abundant; irregular plates of covellite | *b* | |
| 44.9 | 4.9 | 50.2 | Famatinite<br>Argentite<br>Covellite<br>Sulphur | Large idiomorphic crystals of famatinite in eutectic-like growth of argentite and famatinite; famatinite more abundant; more covellite than in preceding specimens | *b* | |
| 40.5 | 5.0 | 54.5 | Famatinite<br>Argentite<br>Covellite<br>Chalcocite<br>Sulphur | Idiomorphic dendrites of famatinite in eutectic-like famatinite and argentite; famatinite more abundant, and rimmed on filming; aggregates of covellite and some chalcocite | *b* | |
| 85.2 | 9.9 | 4.9 | Argentite<br>Phase B<br>Pyrargyrite<br>Covellite<br>Sulphur | Rounded argentite dendrites surrounded by phase B. Interstitial eutectic-like growth of phase B and pyrargyrite; some covellite (certainly less than 0.5 per cent, and probably less than 0.1 per cent) associated with the argentite | *a* | |
| 80.2 | 9.9 | 9.9 | Argentite<br>Phase B<br>Phase C<br>Pyrargyrite<br>Covellite<br>Sulphur | Rounded and irregular argentite dendrites surrounded by phase B. Phase C forms groundmass. A little argentite and pyrargyrite in interstitial eutectic-like structures. A little covellite (less than 0.5 per cent) associated with argentite | *a* | 21 |

* This table is condensed from Table VIII in thesis by one of us.[12] In that table weights of the charges are given, and there is a record of many more charges than in this table.

TABLE VI (*Continued*).

| Composition Atomic Per Cent | | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|
| Ag | Sb | Cu | | | | |
| 75.1 | 9.9 | 15.0 | Argentite<br>Phase B<br>Phase C<br>Famatinite<br>Covellite<br>Sulphur | Argentite dendrites identically orientated, and irregular crystals of phase B surrounded by phase C; some interstitial famatinite and covellite | *a* | 22 |
| 70.0 | 9.9 | 20.1 | Argentite<br>Phase B<br>Phase C<br>Famatinite<br>Sulphur | Oriented dendrites of argentite partly included in aggregates of abundant, large crystals of phase C, and of scarce smaller crystals of phase B. Famatinite interstitial | *c* | |
| 65.1 | 9.8 | 25.1 | Argentite<br>Phase B<br>Phase C<br>Famatinite<br>Covellite<br>Sulphur | Oriented dendrites of argentite partly included in large crystals of phase C. Famatinite and argentite in eutectic-like structure forming groundmass. Phase B as scarce irregular crystals. Specimen not completely homogenized | *c* | |
| 60.0 | 10.0 | 30.0 | Argentite<br>Phase C<br>Famatinite<br>Covellite<br>Sulphur | Rounded argentite dendrites. Large irregular crystals phase C. No phase B. Famatinite and argentite in eutectic-like structure | *a* | |
| 46.7 | 10.4 | 42.9 | Famatinite<br>Argentite<br>Covellite<br>Sulphur | Idiomorphic dendrites of famatinite in a eutectic-like structure with argentite. Famatinite and covellite more abundant than in preceding specimens containing about 10 at. per cent Sb | *a* | |
| 30.1 | 9.9 | 60.0 | Famatinite<br>Argentite<br>Covellite<br>Sulphur | Idiomorphic dendrites of famatinite, in a eutectic-like structure of famatinite with argentite. Covellite increasing in amount | *a* | 23 and 24 |
| 14.9 | 10.0 | 75.1 | Chalcocite<br>Stromeyerite<br>Covellite<br>Famatinite<br>Sulphur | Fossil dendrites of chalcocite largely inclosed in later crystals of famatinite in turn surrounded by eutectic-like growth of famatinite with covellite and largely transformed to stromeyerite and covellite with only trace of residual chalcocite | *a* | |

TABLE VI (*Continued*).

| Composition Atomic Per Cent | | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|
| Ag | Sb | Cu | | | | |
| 72.5 | 12.4 | 15.1 | Phase B<br>Phase C<br>Famatinite<br>Pyrargyrite<br>Sulphur | Phase B in small dendrites as primary phase. Phase C forms groundmass and is the most abundant constituent. Famatinite and pyrargyrite in interstitial eutectic-like intergrowth | *c* | |
| 57.5 | 12.5 | 30.0 | Argentite<br>Phase B<br>Phase C<br>Famatinite<br>Sulphur | Rounded argentite dendrites. Phase B in irregular crystals. Phase C as long crystals and is the most abundant constituent. Famatinite interstitial and in eutectic-like structure with phase C but also as large crystals | *c* | |
| 79.1 | 15.9 | 5.0 | Phase B<br>Pyrargyrite<br>Argentite<br>Sulphur | Phase B as irregular dendrites and in eutectic-like structure with pyrargyrite; argentite in groundmass; pyrargyrite most abundant | *c* | 25 |
| 75.9 | 14.5 | 9.6 | Phase B<br>Phase C<br>Pyrargyrite<br>Argentite<br>Sulphur | Irregular dendrites of phase B, and some crystals of phase C. Eutectic-like groundmass of pyrargyrite and argentite. Pyrargyrite is most abundant constituent | *c* | |
| 65.2 | 15.0 | 19.8 | Phase B<br>Phase C<br>Famatinite<br>Pyrargyrite<br>Sulphur | Phase B in rectilinear dendrites. Phase C in rectilinear crystals, occasionally including phase B, hence later. Phase C is the most abundant constituent. Famatinite occasionally as large crystals but mostly in eutectic-like groundmass with pyrargyrite | *b* | 26 |
| 55.2 | 15.0 | 29.8 | Phase B<br>Phase C<br>Famatinite<br>Pyrargyrite<br>Sulphur | Phase B in rectilinear equidimensional crystals. Phase C in rectilinear bladed crystals (most abundant constituent). Famatinite mostly interstitial in eutectic-like relation with pyrargyrite, but also as large crystals. Famatinite increasing in amount | *c* | 27 |
| 75.1 | 20.0 | 4.9 | Pyrargyrite<br>Phase B<br>Famatinite<br>Sulphur | Coarse eutectic-like intergrowth of famatinite and pyrargyrite; pyrargyrite most abundant. Minute inclusions of phase B | *b* | 28 |
| 65.2 | 19.9 | 14.9 | Famatinite<br>Pyrargyrite<br>Phase B<br>Sulphur | Famatinite dendrites. Pyrargyrite forms groundmass with famatinite. Occasional minute inclusions of phase B | *b* | |
| 74.1 | 24.9 | 1.0 | Pyrargyrite<br>Miargyrite<br>Sulphur | Pyrargyrite forms groundmass. Minute inclusions of miargyrite. No copper minerals | *c* | |

TABLE VI (*Continued*).

| Composition Atomic Per Cent | | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|
| Ag | Sb | Cu | | | | |
| 79.0 | 25.1 | 1.9 | Pyrargyrite<br>Miargyrite<br>Sulphur | Pyrargyrite forms groundmass. Minute inclusions of miargyrite. No copper minerals | *c* | |
| 70.0 | 25.0 | 5.0 | Pyrargyrite<br>Miargyrite<br>Sulphur | Pyrargyrite forms groundmass. Interstitial miargyrite. No copper minerals | *b* | |
| 64.4 | 24.7 | 10.9 | Pyrargyrite<br>Miargyrite<br>Famatinite<br>Sulphur | Pyrargyrite in large irregular areas. Famatinite and miargyrite in eutectic-like inter-growth as inclusions | *b* | |
| 15.0 | 25.0 | 60.0 | Famatinite<br>Pyrargyrite<br>Sulphur | Famatinite (most abundant) forms long dendrites. Pyrargyrite is in a eutectic-like structure with famatinite | *b* | |
| 10.0 | 25.0 | 65.0 | Famatinite<br>Pyrargyrite<br>Chalcostibite<br>Sulphur | Famatinite (most abundant) forms elongated, idiomorphic dendrites. Interstitial eutectic-like structure of famatinite and pyrargyrite. Pyrargyrite is the major constituent. A few inclusions of chalcostibite | *b* | |
| 5.1 | 24.9 | 70.0 | Famatinite<br>Pyrargyrite<br>Chalcostibite<br>Sulphur | Famatinite forms elongated, idiomorphic dendrites. Interstitial eutectic-like structure of famatinite and pyrargyrite. Inclusions of chalcostibite. Note lack of rimming in famatinite upon filming | *b* | 29 and 30 |
| 2.3 | 24.9 | 72.8 | Famatinite<br>Pyrargyrite<br>Chalcostibite<br>Sulphur | Famatinite forms elongated, idiomorphic dendrites and is most abundant constituent. Interstitial eutectic-like structure of pyrargyrite and famatinite. Inclusions of chalcostibite | *b* | |
| 45.2 | 49.8 | 5.0 | Miargyrite<br>Stibnite<br>Famatinite<br>Sulphur | Miargyrite dendrites forming by far the most abundant constituent. Inclusions of stibnite and of famatinite | *b* | |
| 40.1 | 50.0 | 9.9 | Miargyrite<br>Stibnite<br>Famatinite<br>Sulphur | Miargyrite dendrites forming the most abundant constituent. Interstitial stibnite and inclusions of famatinite | *b* | |

*Heat Treatment:*

*a*. Heated to 550° C.; cooled slowly to 300° C. with furnace door sealed; and quenched.

*b*. Heated to 600° C.; cooled slowly to 200° C. with furnace door sealed; then quenched.

*c*. Heated to 600° C.; cooled slowly in furnace. Quenched from 200°.

Of the eleven phases observed, eight answer to the description of known minerals; namely, stibnite, miargyrite, pyrargyrite, argentite, chalcocite, covellite, famatinite, chalcostibite. No definite evidence of tetrahedrite was obtained, but this matter was not further investigated as it was but of indirect importance to the problem at hand. Some stromeyerite was formed but the evidence in this direction could have been better. Good crystals of phase B (previously described) were obtained in numerous instances, and an additional phase, referred to here as phase C, was discovered.

*Discussion of Phases.*

The evidence obtained indicates that at the temperatures of freezing of the melts the following solid solutions are obtained:

(*a*) Pyrargyrite dissolves a small amount of copper (perhaps up to 5 atomic per cent), probably as a replacement of silver by copper.

(*b*) Phase B dissolves copper (up to approximately 5 to 7 atomic per cent) as a replacement of silver atoms by copper.

(*c*) Phase C is probably somewhat variable as to copper-silver ratio; that is, it may be regarded as a solid solution varying about a mean.

(*d*) Famatinite dissolves silver and displays its silver content beautifully in rims that film in the silver-filming solution whereas the cores of the crystals remain unfilmed. Incidentally, famatinite made in contact with chalcocite, and that made in contact with chalcostibite do not film at the same rate with the $CrO_3$–HCl–$H_2O$ solution, indicating again that the famatinite phase is a solid solution ranging about a mean.

(*e*) It is not definitely known whether any of the other minerals in this system display solid-solution properties with reference to any of the elements in this system, but it is suspected that argentite, chalcocite and stibnite at least, do so to a considerable extent.

Inasmuch as phase B has been taken up in the pseudo-binary silver sulphide-antimony sulphide, discussion in this section is limited to those phases containing silver that do not arise in that

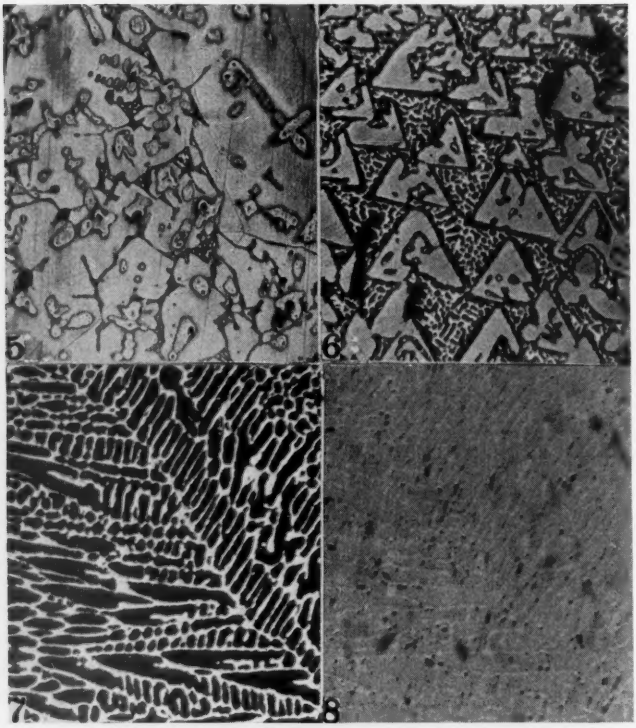

FIG. 5. Rounded argentite dendrites in groundmass of phase A with some interstitial proustite containing minute blebs of smithite. Colors: Argentite, pale blue I to pale yellow II (variegated light gray); phase A, orange-brown I (smooth pale gray); proustite, brilliant blue I (darkest gray); smithite, white. Filmed 20 sec. ×76.

FIG. 6. Dendrites of phase A arranged in regular pattern and surrounded by proustite; groundmass is a eutectic of proustite and smithite. Colors: as in Fig. 5. Filmed 20 sec. ×76.

FIG. 7. Eutectic of proustite and smithite. Colors: Proustite, brilliant blue I (in photograph, dark gray); smithite, white. Filmed 20 sec. ×152.

FIG. 8. Same field as Fig. 6, unfilmed. Two phases can be identified in the photograph, but not visually.

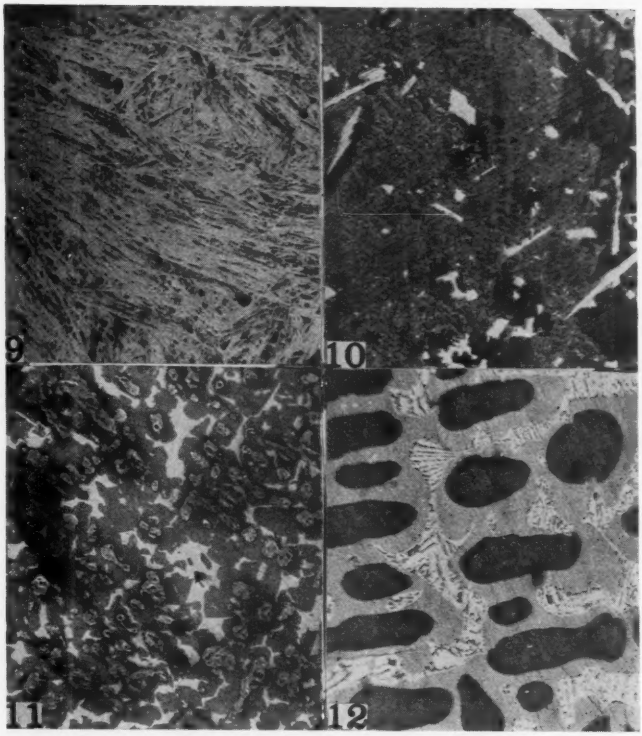


FIG. 9. Sheaf-like aggregates of smithite crystals with some interstitial proustite. Colors as in Fig. 7. Filmed 20 sec. ×76.

FIG. 10. Idiomorphic silver crystals in a groundmass of small argentite dendrites and proustite (sulphur-poor). Colors: Metallic silver, very faint lavender (white); argentite, yellow II (darker gray); proustite, bright blue (lighter gray). Filmed 35 sec. ×380.

FIG. 11. Argentite dendrites surrounded by phase B with interstitial pyrargyrite. Colors: Argentite, blue I to yellow II (mottled gray); phase B, purple brown (medium uniform gray); pyrargyrite, pale yellow (white). Filmed 20 sec. ×76.

FIG. 12. Argentite dendrites surrounded by phase B with interstitial eutectic-like structure of much pyrargyrite and a little argentite. Colors: Argentite, dark blue I (dark gray); phase B, brown (light gray); pyrargyrite, pale yellow (white). Filmed 15 sec. ×300.

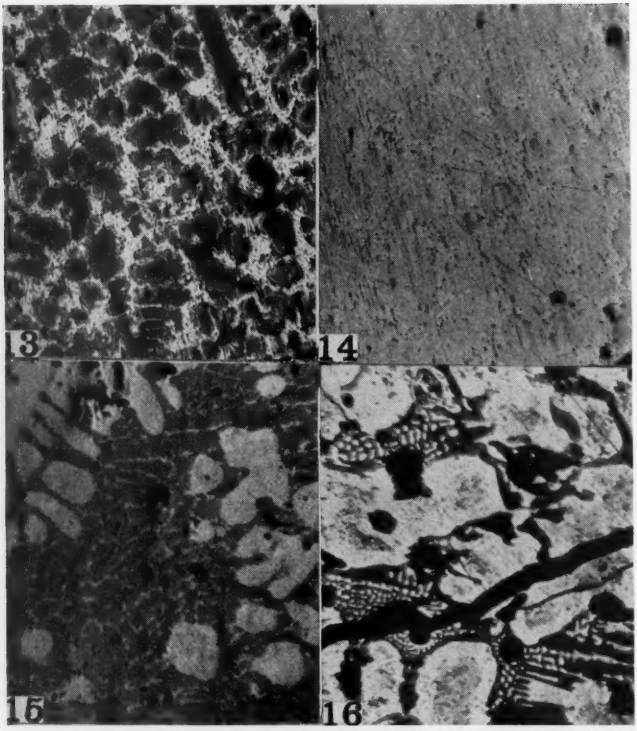


FIG. 13. Argentite dendrites surrounded by phase B with interstitial eutectic-like structure of much pyrargyrite and a little phase B (cf. Fig. 12). Colors: Argentite, blue I (gray in high relief); phase B, purplish-brown (gray, no relief); pyrargyrite, pale yellow (white). Filmed 18 sec. × 76.

FIG. 14. Same field as Fig. 13, no filming. (Note position of pits in this and Fig. 13.)

FIG. 15. Irregular, rounded dendrites of miargyrite in eutectic of much pyrargyrite with some miargyrite. Colors: Pyrargyrite, pale yellow I (gray); miargyrite, white (somewhat mottled to very pale gray in places because of translucence under oil-immersion). Filmed 20 sec. × 300.

FIG. 16. Irregular dendrites of miargyrite in eutectic of miargyrite with stibnite. Note ex-solution precipitation of stibnite at core of miargyrite grains. Colors: Stibnite, purple-brown (gray); miargyrite, grayish white (white). The black band in the center and black rounded areas are pits. Filmed 25 sec. in $CrO_3$-HCl-$H_2O$ solution. × 300.

binary system; namely, phase C, stromeyerite and argentiferous famatinite. In addition some discussion is in order of the cupriferous pyrargyrite and cupriferous phase B.

*Stromeyerite* films very much like argentite. For a long time this led to overlooking this phase, especially as no low-power oil-immersion objective was available, the use of which definitely permits differentiation between isotropic argentite and anisotropic stromeyerite. The reaction of stromeyerite and argentite to the standard silver-filming solution is much the same, although the variegated rim typical of argentite is not found on stromeyerite. In addition there is some slight color difference between these minerals in the filmed condition, but considerable practice is required to make identification certain.

*Phase C* is definitely anisotropic in both the unfilmed and filmed condition. This characteristic sets off phase C from phase B which it otherwise resembles in filming colors. The resemblance in filming color, however, is by no means an identity as may be seen by referring to the identification guide. Since phase C does not occur in the pseudo-binaries that bound the pseudo-ternary it is likely, *a priori*, that the phase in question contains all four of the elements; namely, copper, silver, antimony, and sulphur.

Determinations of a semi-quantitative nature were made as to the content of silver, copper and antimony in phase C. These determinations consisted of estimates made under the microscope of the relative abundance of the various phases present in specimens rich in phase C. Determinations made by other observers all agreed in pointing to an atomic ratio of the metallic elements of 12 silver, 3 copper, and 2 antimony. Writing this in another way the formula might be $6Ag_2S \cdot 3CuS \cdot Sb_2S_x$ or $12Ag_2S \cdot 3Cu_2S \cdot 2Sb_2S_y$. In these formulæ $x$ and $y$ are 3 or 5. Of the two formulæ the first is simpler; it is preferable, further, in that phase C was never formed in the absence of excess sulphur so that cupric copper is more likely than cuprous copper.

No natural mineral is regarded to have such a formula as is here deduced for phase C. Since polybasite is the only natural mineral containing both copper, silver and antimony sulphides, it

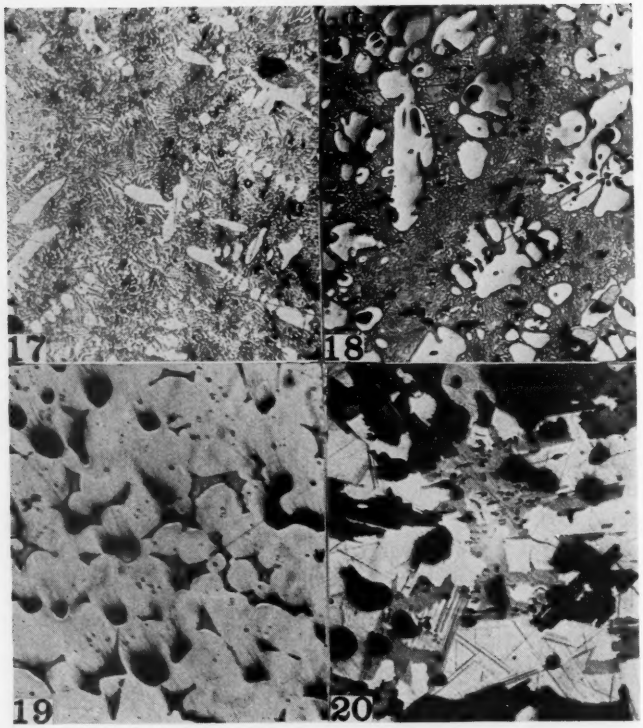


FIG. 17. Rounded dendrites of argentite in characteristic eutectic of argentite and phase D. Argentite is the more abundant constituent. Colors: Argentite, brilliant pale yellow II (white) and phase D, orange I (gray). Filmed 20 sec. × 76.

FIG. 18. Rounded irregular dendrites of phase D in eutectic of phase D and argentite. Phase D is the more abundant constituent. Colors: Argentite, dark blue I (gray), phase D, yellow I (white). Filmed 15 sec. × 76.

FIG. 19. Consists almost wholly of phase D with minor quantities of interstitial argentite. Colors: as in Fig. 18. Filmed 20 sec. × 300.

FIG. 20. Matildite with included bismuthinite; note characteristic twinning. Colors: Bismuthinite, white; matildite, yellow, orange or purple according to crystallographic orientation (light to dark gray). Filmed with hydrochloric acid-iodine-methyl alcohol solution.

may be profitable to compare phase C with it. Both are anisotropic. The color of the unfilmed phases agrees, insofar at least as perceptions by different observers as to color of natural minerals ever agree. The specimen of polybasite of the U. S. Geological Survey to which reference has already been made and which contains many different things, does contain a substantial amount of a phase that films very much like phase C. One may, therefore, tentatively correlate phase C with polybasite although such a correlation cannot be regarded as conclusive.

*Argentiferous Famatinite.*—Upon immersion in the standard silver-staining solution the famatinite formed in eutectic-like intergrowths in this system acquires practically the same blue color as argentite in 15 seconds. This has led at times to mistaking argentiferous famatinite for argentite (in eutectic-like intergrowths).

Large crystals of famatinite do not film at all in the silver filming solution except at their rims where a beautiful gradational filming may be observed. This was observed in all cases where famatinite was present with argentite or with phase B. It was observed also in all cases of famatinite in contact with pyrargyrite except when chalcostibite was also present. It was not observed where famatinite was present with miargyrite.

This rim-filming may be due to one of two causes; namely, the formation of a fluid film flowing over the famatinite from neighboring crystals or the presence in the famatinite, in solid solution, of silver atoms in gradually increasing proportion from core to rim. In choosing between the two it is useful to note the remarkable wedge-shape of the iridescent film on the rims of the famatinite (ascertained from the distance of points where the film has certain typical colors [3a]), a condition that would be directly explained by the solid-solution idea but which is not so readily met by the other hypothesis. It may further be remarked that the width of the wedge-shaped rims on the famatinite increases with time of filming, another observation that favors the solid-solution theory. Furthermore, there is no particular ground for assuming that a fluid film should be available to spread over

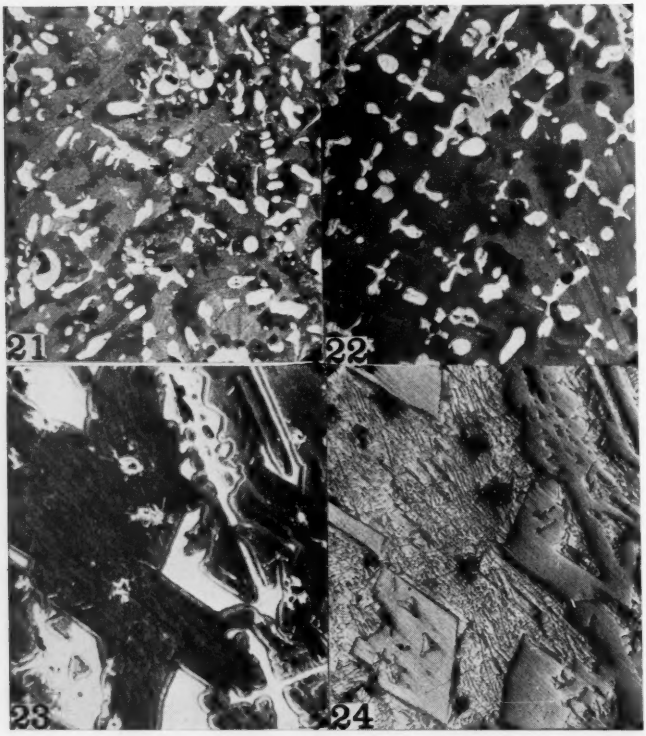


FIG. 21. Rounded argentite dendrites surrounded by phase B in continuous groundmass of phase C. Colors: Argentite, pale blue I to pale yellow II (white) and phase B, maroon I (gray), phase C, purple (medium gray; smoother and paler than the gray of phase B). Filmed 20 sec. ×76.

FIG. 22. Rounded argentite dendrites identically orientated in a groundmass mostly of phase C but also with some phase B and famatinite. Colors: as in Fig. 21. The famatinite (pale gray) can be told from the argentite by its less smooth surface, and non-dendritic form. Filmed 20 sec. ×76.

FIG. 23. Idiomorphic dendrites of famatinite in a eutectic-like structure of famatinite and argentite, some bundle-like covellite plates. Colors: Famatinite idiomorphs, core white (white), outer edge, blue I grading

the famatinite while it fails to spread over other neighboring crystals. Finally, the films are not formed if antimony is available in excess of the 1 : 3 atomic proportion (in reference to copper + silver). This suggests that the solid solution of silver in famatinite is of the additive rather than of the substitutive type.

*Cupriferous Phase B and Cupriferous Pyrargyrite.*—In some of the specimens formed while copper was added to the charge, no obvious copper-bearing minerals were formed. The copper must then have become hidden in solid solution. In this way it was ascertained that copper may be dissolved in phase B and in pyrargyrite and a rough estimate of the magnitude of this effect was reached.

### *Discussion of Structures.*

The following occur as primary phases: stibnite, miargyrite, pyrargyrite, phase B, argentite, chalcocite, and famatinite. Phase C, stromeyerite and covellite have never been observed as primary phases. Tetrahedrite and chalcostibite, likewise, have not been obtained as primary phases but our evidence is not conclusive on that score whereas it is believed to be conclusive in connection with phase C, stromeyerite and covellite. Fig. 4 delineates the boundary lines of the primary phases in this system. These boundary lines are drawn full whenever they have been accurately surveyed, and dotted otherwise. Each circle represents a specimen that was prepared and the abbreviation denotes the primary phase that was observed. The numbers have no special reference to this paper.

In addition to the structures which have already been recorded

toward the core through dark blue I, purple I, brown I, and tan I. The darkest zone is purplish-brown, I. Famatinite in eutectic slate-blue I, argentite blue I (gray); covellite, pink (pale gray). Filmed 20 sec. ×76.

FIG. 24. Colors: Famatinite, pinkish pale gray, in high relief; argentite, bluish white; covellite, blue (dark gray). Most of the differentiation between famatinite and argentite is due to relief. Same field as Fig. 23, unfilmed. ×76.

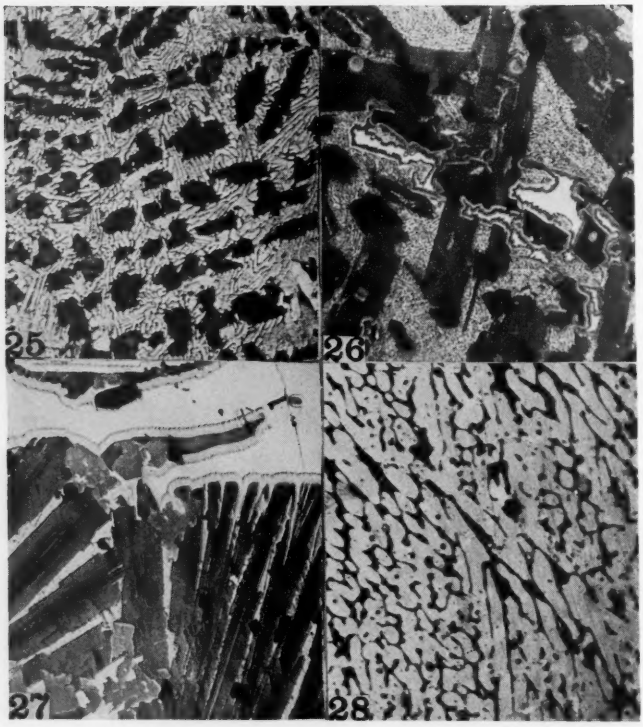


FIG. 25. Phase B as irregular dendrites and in eutectic-like structure with pyrargyrite. Colors: as in Fig. 21. Filmed 20 sec. ×76.

FIG. 26. Phenocrysts of phases B and C, occasional large crystals of famatinite in fine grained eutectic-like intergrowth of famatinite and pyrargyrite. This is one of the most typical photographs showing phase C. Colors: Phase B, maroon I (dark gray); phase C, purple (medium gray); famatinite, white in core grading to blue I at rim (white at core and gray at rim); pyrargyrite, yellow I (very pale gray). Filmed 20 sec. ×76.

FIG. 27. Unusual field showing large famatinite crystal in contact with primary crystals of phase B, later bladed crystals of phase C, and eutectic-like intergrowth of famatinite with pyrargyrite. Colors: Substantially as in Fig. 26. In this photograph, however, phase C appears slightly darker than phase B. Filmed 20 sec. ×76.

for the various binary systems, the following observations are in order:

*Miargyrite* occurs with inclusions of famatinite.

*Pyrargyrite* occurs in eutectic-like intergrowths with famatinite.

*Phase B* occurs as primary dendrites occluded in large crystals of phase C.

*Argentite* occurs as dendrites occluded in large crystals of phase C; as dendrites occluded in a eutectic-like growth of famatinite and phase C, characterized by long bladed crystals of phase C. Argentite is also found in eutectic-like structures with famatinite.

*Stromeyerite* has not been observed except in one or two instances as a decomposition product of what must have been argentiferous chalcocite.

*Phase C* occurs as crystals conspicuously large in relation to all other crystals in the same specimen. Commonly they include argentite dendrites or phase B dendrites, or both. In other instances they occur in a groundmass of finely intergrown pyrargyrite and famatinite. Phase C is also observed in plate-like eutectic or eutectoid structures with famatinite. In some cases genetic relations of phase C to argentite plus famatinite are not altogether clear; either the pair has resulted from a breakdown of phase C or phase C has grown from adjoining grains of argentite and famatinite by reaction in the solid state.

*Famatinite* occurs either in characteristic dendrites or in eutectic-like intergrowths with argentite, pyrargyrite, miargyrite or phase C.

*Chalcocite* is generally residual and replaced by covellite, or if argentiferous in the first place, by covellite and stromeyerite. The original chalcocite was, of course, dendritic. It is commonly occluded in famatinite.

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FIG. 28. Typical coarse eutectic-like intergrowth of famatinite and pyrargyrite. Colors: Pyrargyrite, yellow I (light gray); famatinite, dark blue I (dark gray). The famatinite here is all rim substance. Although appreciably coarse, the structure in the specimen is substantially like that of the eutectic-like intergrowths in 26, 27 and others. Filmed 20 sec. × 160.

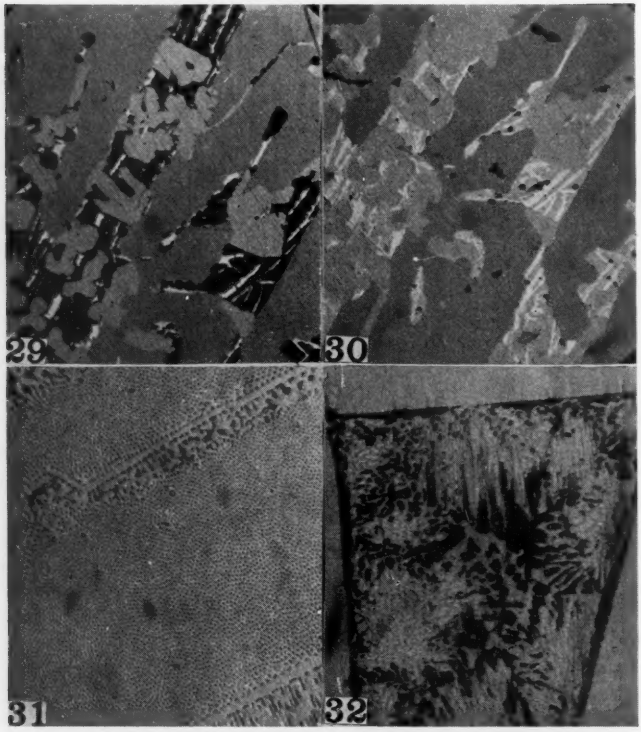


FIG. 29. Aggregates of famatinite crystals cut in various orientations and containing inclusions of pyrargyrite and chalcostibite. Colors: Famatinite, pinkish white of various shades (various shades of light gray); chalcostibite, white; pyrargyrite, brownish yellow I (dark gray). Note pleochroism of famatinite. Filmed 30 sec. × 76, plane polarized light.

FIG. 30. Note contrast in shade of famatinite crystals in different orientations and absence of color difference between the light famatinite and pyrargyrite. Cf. Fig. 29. Same field, unfilmed. × 76, plane polarized light.

FIG. 31. Ex-solution precipitation of covellite in phase A. Colors: Covellite, blue (gray); phase A, tan-cream (gray). Unfilmed. × 160.

FIG. 32. Inter-crystalline eutectic-like intergrowth of stromeyerite, covellite and phase A between large crystals of phase A. Colors: Covellite blue (very dark gray); phase A, tan-cream (gray), stromeyerite, pale gray (pale gray). Unfilmed. × 160.

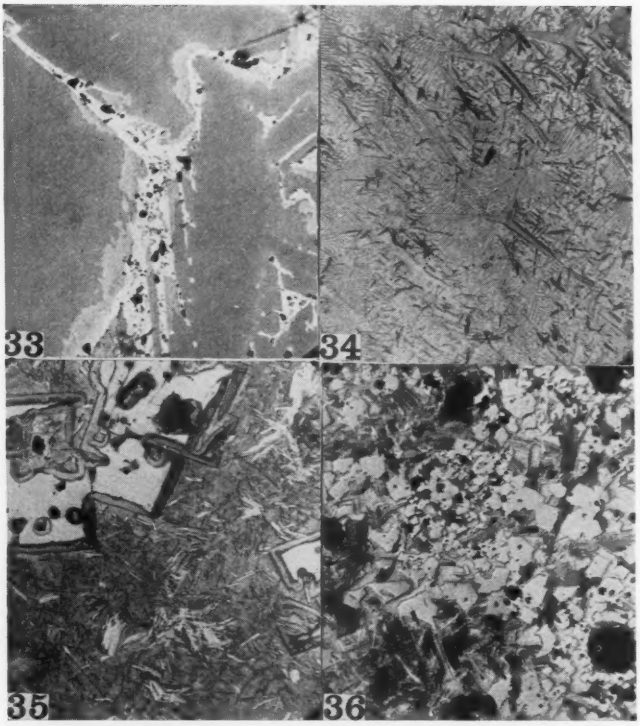


FIG. 33. Crystals of phase A with rims of stromeyerite, and separated by interstitial covellite and stromeyerite. Colors: Stromeyerite, pale blue I (pale gray); covellite, pink I (white); phase A, purple-brown I (medium gray). Filmed 20 sec. ×76.

FIG. 34. Dendritic crystals of phase A in stromeyerite, a few plates of covellite. Colors: Phase A, pale gray with rose-tan cast (pale gray); stromeyerite, white with a bluish cast (palest gray); covellite, blue (dark gray). Unfilmed. ×76.

FIG. 35. Idiomorphic crystals of enargite in groundmass of fine intergrowth of stromeyerite and enargite with bundles of covellite crystals. Colors: Enargite, white I in core with rims grading to blue I through tan and purple (white in core with gray rims); covellite, pink of various shades according to crystal orientation (pale gray); stromeyerite, blue I (medium gray). Filmed 20 sec. ×76.

FIG. 36. Equidimensional grains of enargite in a groundmass of stromeyerite and covellite. Colors: as in Fig. 35. Filmed 20 sec. ×76.

## SILVER SULPHIDE-ARSENIC SULPHIDE-COPPER SULPHIDE SYSTEM.

No data are available in the chemical literature concerning this system. Although the system is more complex than a ternary, it is treated as such in this paper. The data that are presented are both preliminary and incomplete. However, they establish the lack of an arsenical counterpart to phase C.

The data for two of the pseudo-binaries that form the boundaries of this pseudo-ternary system have already been presented. No data are obtainable on the system copper sulphide-arsenic sulphide.

In addition to the minerals in the two binary systems that have already been taken up, mineralogists recognize two sulpharsenides of copper, tennantite, $3Cu_2SAs_2S_3$, and enargite, $3Cu_2SAs_2S_5$. The formula for tennantite is not incontrovertibly established.

### *Discussion of Phases.*

*Argentite* has all the characteristics observed in previous systems.

*Phase A* (although exhibiting the same characteristics as previously observed in the pseudo-binary silver sulphide-arsenic sulphide system) apparently has the ability to retain an appreciable amount of copper sulphide in solution. Ex-solution of covellite and stromeyerite occurs.

*Stromeyerite* appears identical to the natural mineral. No natural stromeyerite was available for comparison; but from the characteristics as recorded by mineralogists, it can be concluded that the synthetic product is stromeyerite.

The interference colors observed were identical to those observed on stromeyerite occurring in the silver sulphide-antimony sulphide-copper sulphide pseudo-binary system.

Synthetic *enargite* exhibits all the characteristics of the natural mineral. On filming enargite, rims are observed indicating silver content. For the same reasons as for famatinite, silver sulphide is probably soluble to some extent in enargite at its freezing point.

No tennantite was observed. In all probability the fact that

these specimens were prepared in the presence of excess sulphur is responsible for the perferential formation of enargite. In fact tennantite has been synthesized by others at Montana School of Mines.

### *Discussion of Structures.*

The structures are described in Table VII. Since some of the phases occurring in this system were observed in the silver sulphide-arsenic sulphide pseudo-binary system, a repetition is unnecessary.

*Stromeyerite* occurs as ex-solution blebs, as a part of a ternary eutectic-like structure with phase A and covellite; in ternary eutectic-like structure with covellite and enargite, and as coronas about primary crystals of phase A.

*Enargite* occurs as idiomorphic dendrites, as equi-dimensional grains with chalcocite and in a ternary eutectic-like intergrowth with covellite and stromeyerite.

## IDENTIFICATION GUIDES.

Table VIII presents the color sequence generally obtained by iridescent filming. Although the sequence is the same, the exact shade of color is not the same with all minerals, since that result would not be obtained unless the films were equally absorbing for all wave-lengths of light, unless the substrata were reflecting equally all wave-lengths, and unless certain other optical requirements were met.[3a] Practically speaking, deviations from Table VIII are slight.

Table IX is the identification guide. It presents in summary form the observations on color of filmed surfaces to which reference has been made here and there through this paper. The colors given are those observed with ordinary lenses. The colors under oil immersion are generally darker and more contrasting.

The photographs were all taken with low-power oil immersion objectives on Kodak panchromatic film with a Leica camera.

TABLE VII.

SELECTED DESCRIPTIVE LIST OF SPECIMENS PREPARED IN THE SILVER SULPHIDE-ARSENIC SULPHIDE-COPPER SULPHIDE SYSTEM WITH EXCESS SULPHUR

| Composition Atomic Per Cent | | | Phases | Structure | Heat | Figure |
|---|---|---|---|---|---|---|
| Ag | Sb | Cu | | | | |
| 80.0 | 10.0 | 10.0 | Phase A<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic crystals of phase A; interstitial eutectic-like intergrowths of phase A and stromeyerite. Ex-solution blebs of stromeyerite and covellite arranged along crystallographic planes | *a* | 31 and 32 |
| 70.0 | 10.0 | 20.0 | Phase A<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic crystals of phase A; groundmass composed of a ternary eutectic-like structure of phase A, stromeyerite, and covellite. Phase A is the most abundant constituent | *a* | |
| 60.0 | 10.0 | 30.0 | Phase A<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic dendrites of phase A. Ex-solution blebs of stromeyerite. Ternary eutectic-like structure of phase A, stromeyerite, and covellite. Phase A is the most abundant constituent | *a* | |
| 50.0 | 10.0 | 40.0 | Phase A<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic crystals of phase A with coronas of stromeyerite. Interstitial covellite and stromeyerite | *a* | 33 |
| 40.0 | 10.0 | 50.0 | Enargite<br>Phase B<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic dendrites of enargite. Crystals of phase B occasionally surrounding enargite as if isomorphous with it, and often dendritic. Groundmass of ternary eutectic-like intergrowth of enargite, stromeyerite, and covellite | *a* | 34 |
| 30.0 | 10.0 | 60.0 | Enargite<br>Stromeyerite<br>Covellite<br>Sulphur | Idiomorphic dendrites of enargite. Groundmass is a ternary eutectic-like growth of enargite, stromeyerite, and covellite | *a* | 35 |
| 20.0 | 10.0 | 70.0 | Enargite<br>Stromeyerite<br>Covellite<br>Sulphur | Equidimensional grains of enargite. Interstitial covellite and stromeyerite. Increasing amount of covellite | *a* | 36 |
| 10.0 | 10.0 | 80.0 | Enargite<br>Stromeyerite<br>Covellite<br>Sulphur | Small equigranular grains of enargite. Groundmass consists of a very little stromeyerite and considerable covellite | *a* | |

*Heat Treatment:*

*a*. Heated to 560° C.; cooled slowly to 160° C. by sealing door of furnace; then quenched.

TABLE VIII.

COLOR SEQUENCE TABLE.*

| | | Order |
|---|---|---|
| Unfilmed | White (uncolored) | |
| Filmed | Pale tan to yellow | |
| | Tan to orange | |
| | Purplish brown to purple | I |
| | Dark blue | |
| | Pale blue | |
| | Whitish blue to whitish yellow—"Hiatus" | |
| | Yellow | |
| | Brilliant crimson | II |
| | Blue | |
| | Brilliant green | |
| | Yellowish green | |
| | Old rose | III |
| | Slate blue | |
| | Green | |
| | Etc. | IV |

Increasing thickness of film

* For a fuller discussion reference can be made to the article by one of us.[30]

SUMMARY.

A number of sulphide minerals have been synthesized by melting together in bombs various elements with sulphur.

The following silver minerals were thus prepared:

Argentite.
Proustite.
Smithite.
Pyrargyrite.
Miargyrite.
Matildite.

Stromeyerite.

In addition, four other silver compounds were synthesized. These are termed phases A, B, C and D. It is probable that they are identical, respectively, with the minerals,

Pearcite.
Stephanite
Polybasite.
Tapalpite.

At the same time as these silver minerals, a number of other sulphides were synthesized; namely,

Chalcocite.
Covellite.
Famatinite.
Tetrahedrite.
Chalcostibite.
Stibnite.
Arsenic sulphide.
Galena.
Enargite.
Bismuthinite.

TABLE IX.

IDENTIFICATION GUIDE. FILMING COLORS WITH STANDARD SOLUTION OBSERVED WITH LOW POWER OBJECTIVES. DURATION OF EXPOSURE TO STANDARD SILVER FILMING SOLUTION AT 18–20° C.

| Phases | 10 Seconds | 15 Seconds | 20 Seconds | 30 Seconds | 45 Seconds | 1 Minute | 2 Minutes |
|---|---|---|---|---|---|---|---|
| Argentite..... | DARK BLUE (I) Grading to purple (I), blue (I) | BLUE (I) Grading to dark blue (I), light blue (I) | LIGHT BLUE (I) Grading to blue (I), pale yellow (II) | WHITISH YELLOW (II) Grading to pale blue (I), yellow (II) | YELLOW (II) Grading to light yellow (II), crimson (II) | CRIMSON (II) Grading to higher-order colors | |
| Phase A..... | TAN (I) | DARK TAN (I) | ORANGE-BROWN (I) Grading to lavender (I) | ORANGE-BROWN (I) Grading to lavender (I), purple (I) | PURPLE (I) | BLUISH PURPLE (I) | |
| Proustite..... | —— | PURPLE (I) | DARK BLUE (I) Grading to brilliant purple (I) | BLUE (I) | BLUISH GREEN (I) | LIGHT GREEN‡ (hiatus) | |
| Smithite..... | —— | —— | WHITE | WHITE | WHITE | VERY PALE YELLOW (I) | VERY PALE YELLOW (I) |
| Phase B..... | TAN (I) | DARK TAN (I) | BROWN PURPLE (I) Grading to light brown (I) | PURPLE (I) Grading to light lavender (I) | LAVENDER (I) | LAVENDER (I) Grading to blue (I) | YELLOW (II) |
| Pyrargyrite... | WHITE | VERY PALE YELLOW (I) | LIGHT YELLOW (I) | LIGHT YELLOW (I) | LIGHT BROWN (I) | LIGHT BROWN (I) | BLUE (I) |
| Miargyrite.... | —— | —— | WHITE | WHITE | YELLOWISH WHITE (I) | YELLOWISH WHITE (I) | —— |
| Stromeyerite.. | —— | —— | PALE BLUE (I) | —— | —— | —— | —— |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Stromeyerite.. | —— | —— | PALE BLUE (I) | —— | —— | —— | —— |

TABLE IX (*Continued*).

| Phases | 10 Seconds | 15 Seconds | 20 Seconds | 30 Seconds | 45 Seconds | 1 Minute | 2 Minutes |
|---|---|---|---|---|---|---|---|
| Phase C..... | —— | —— | PURPLE<br>Grading to violet (I), reddish purple (I) | DARK BLUE (I)<br>Grading to purple (I), light blue (I) | LIGHT BLUE (I)<br>Grading to light yellow (II) | LIGHT YELLOW (II)<br>Grading to light blue (I) | To high order colors |
| *Covellite.... | —— | —— | PINK; in certain orientations light blue | PINK; in certain orientations light blue | PINK; in certain orientations blue | LIGHT PINK; in certain orientations blue, purple, red | LIGHT PINK; in certain orientations blue, purple, red |
| Phase D..... | YELLOW (I) | —— | ORANGE (I) | ORANGE (I) | ORANGE (I)<br>Grading to purple (I) | LIGHT PURPLE (I)<br>Grading to light blue (I) | PURPLE (I) |
| Matildite..... | WHITE | WHITE | WHITE | WHITE | WHITE | WHITE | WHITE |
| Chalcocite.... | BLUE (I)<br>Grading to dark blue (I) | BLUE (I)<br>Grading to dark blue (I), light blue (I) | LIGHT BLUE (I)<br>Grading to blue (1), dark blue | LIGHT BLUE<br>To high order colors | To high order colors | To high order colors | To high order colors |
| † Other sulphides... | —— | —— | —— | —— | —— | —— | —— |

* Covellite has such a highly selective light absorption that a very unorthodox sequence of interference colors for filmed surface should be expected.[30]

† The following other sulphides fail to acquire color on exposure to the standard silver filming solution, at least up to 5-minute exposures: stibnite, bismuthinite, famatinite (if not silver-bearing), tetrahedrite, chalcostibite.

‡ See Table VIII.

By comparison with Clarke's Data of Geochemistry [17] in which most of the early attempts at mineral synthesis are recorded, it will be seen that this paper discloses the synthesis, for the first time, of a number of interesting sulphides.

The structural relationships of the various phases were studied in some detail.

The determinative method of selective iridescent filming is extended to silver minerals by devising a suitable filming solution. A systematic identification guide for the determination of silver minerals, using the standard filming solution, is presented.

Comparison was made whenever possible between the synthesized standards and natural minerals not only in respect to the usual mineralogical criteria but also in respect to iridescent filming.

Corrections in the accepted formulae for some of the minerals have been proposed.

MINERAL DRESSING DEPARTMENT,
MONTANA SCHOOL OF MINES,
BUTTE, MONTANA,
*Nov. 30, 1937.*

LITERATURE CITED.

1. *a.* GAUDIN, A. M.: Staining for easier identification in quantitative mineragraphic problems. ECON. GEOL., vol. 30, pp. 552–562, 1935.
*b.* HENDERSON, H. B.: Laboratory report to A. M. Gaudin on "Copper Sulfarsenides and Sulfantimonides in Butte ores." 1932.
*c.* GAUDIN, A. M., AND MALOZEMOFF, PLATO. A preliminary study of the copper-nickel ore from Falconbridge, Ont., from the standpoint of ore dressing. Mont. Sch. Mines, 1932.
*d.* GAUDIN, A. M.: The identification of sulphide minerals by selective iridescent filming. Gluck Auf, vol. 1, no. 5, pp. 5–6, 1936.
2. SWILER, W. R.: Differentiation under the microscope of natural and synthetic minerals by selective iridescent staining. Thesis, Mont. Sch. Mines, 1935.
3. *a.* GAUDIN, A. M.: The identification of opaque solids by selective iridescent filming. Part I—Optics, Jour. Physical Chem., June 1937. (A complete bibliography is included.)
*b.* Idem. Part II—"Physical Chemistry and Crystallography." In preparation.
4. *a.* EVANS, U. R., AND BANNISTER, L. C.: The growth of silver iodide films. Roy. Soc. London, Proc., vol. A 125, pp. 370–94, 1929.
*b.* EVANS, U. R.: Die Interferenzfarben duenner Filme von oxyden, Sulfiden and Iodiden von Metallen. Kolloid Zeitschr., vol. 69, pp. 129–37, 1934.

5. *a.* TAMMANN, G., AND KOESTER, W.: Die Geschwindigkeit der Einwirkung von Sauerstoff, Schwefelwasserstoff and Halogenen auf Metalle. Zeitschr. fur anorganische Chemie, vol. 123, pp. 196–224, 1922.
*b.* TAMMANN, G., AND BREDEMEIER, H.: Ueber die Einwirkung von Sauerstoff und Halogenen auf metallische Mischkristalle, Metalle und binaere Verbindungen. Zeitschr. fur anorganische Chemie, vol. 136, pp. 337–57, 1924.
6. MEHL, ROBERT F., AND WELLS, CYRIL: Constitution of high-purity iron-carbon alloys, Am. Inst. Min. Met. Eng., Techn. Pub. No. 798, 1937.
7. *a.* JAEGER, F. M.: Natural and artificial sulfoantimonites and sulfoarsenites. Orig. Com. 8th Intern. Congr. Appl. Chem., vol. 2, pp. 139–63, 1912.
*b.* JAEGER, F. M.: Sulfoantimonites. Kgl. Akad. Wetenschappen, vol. 20, pp. 510–6, 1912.
*c.* JAEGER, F. M., AND VAN KLOOSTER: Z. Anorg. und allg. Chem., vol. 78, p. 245, 1912.
8. GEN KEMURA: The transition and thermodynamic values of silver sulphide. Bull. Inst. Phys. Chem. Research, Tokyo, vol. 13, pp. 464–74, 1934.
9. DANA, E. S., AND FORD, W. C.: Dana's textbook of mineralogy, 4th ed., pt. II.
10. SCHNERDERHOEHN, H., AND RAMDOHR, P.: Lehrbuch der Erzmikroskopie. Gebr. Borntraeger, Berlin, 1931.
11. SHORT, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv., Bull. 825, Pt. II, 1931.
12. MCGLASHAN, DONALD W.: Sulphide silver-bearing minerals. A contribution to their pyrosynthesis and to their identification by selective iridescent filming. Dissertation. Mont. Sch. Mines, 1937.
13. KONNO, KOSUKE: Metallographic investigation of the system antimony sulfide-silver sulfide. Memoirs College Science, Kyoto Imp. Univ., vol. 4, pp. 51–4, 1919.
14. FRIEDRICH, K.: The melting point curves of the systems galena-pyrrhotite and of galena-silver sulfide. Metallurgie, vol. 4, p. 479, 1907.
15. SCHWARTZ, G. M.: Relations of chalcocite-stromeyerite-argentite. ECON. GEOL., vol. 30, pp. 128–46, 1935.
16. *a.* PARRAVANO, N.: Gazz. Chim. Italiana, vol. 39, ser. II, p. 55, 1909.
*b.* PARRAVANO, N., AND DE CESARIS, P.: Cuprous sulfoantimonites. Atti. accad. Lincei, vol. 21, ser. I, pp. 798–802, 1912.
17. CLARKE, F. W.: The data of geochemistry, 5th ed., U. S. Geol. Surv., Bull. 770.

# LATE GOLD AND SOME OF ITS IMPLICATIONS.

J. B. MAWDSLEY.

ABSTRACT.

In many Canadian gold deposits the gold is one of the last minerals deposited. In some cases, considerable time has elapsed between its introduction and that of the other minerals; in others, a subordinate amount of gold was introduced with at least some of the other minerals, but the main gold enrichment was later.

The tentative hypothesis is advanced that in such cases the bulk of the vein material left the magma before the gold. This early magmatic product left in the gaseous state but condensed to a liquid prior to its final deposition; the gold remained behind and was concentrated in the liquid end-product of the magma. The early gaseous phase when condensed to a liquid phase rich in super-heated water, could dissolve, transport and deposit much silica and account for much of the vein quartz. The cases in which both early and late gold are present are explainable on the basis of the partial intermingling of the two magmatic products.

Distinctly late gold raises the question of the soundness of classifying many gold deposits on the basis of their associated vein minerals. The occurrence of gold-bearing ore shoots is often easily explainable, assuming gold to be late, by inferring late stresses resulting in suitable structures. Weak members, such as vein quartz, are loci for such favorable channels.

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## INTRODUCTION.

THAT gold is often the last metal to be deposited in metal-bearing ore deposits has long been recognized. That it is, in many cases, distinctly later than, and not closely related to, the associated vein materials, is not so generally admitted. During the last few years, this latter aspect of the matter has been brought forcibly to the writer's attention. The following paper briefly describes a few typical examples, cites some inferences, advances a tentative explanation, and suggests in turn some further deductions.

## SOME EXAMPLES OF LATE GOLD.

The following examples of distinctly late gold are a few that have been studied by the writer or brought to his attention. There are other cases in which the writer believes the same age relationship exists, but the following examples will suffice to indicate the occurrence and the widespread distribution of late gold, at least in the pre-Cambrian formations of Canada. The detailed petrological study of such a deposit has recently been discussed by Hawley.[1]

### *Rouyn-Siscoe Area, Quebec.*

*O'Brien.*—An outstanding example is the free gold occurring in the spectacularly high grade ore mined at the O'Brien Gold Mines Limited's property, Cadillac Township, Quebec. In this case, in many specimens from the high grade sections of the quartz vein, the gold is seen to be more or less concentrated along the centre of the vein and along numerous parallel fractures that lie almost at right angles to the strike of the vein. These transverse films or veinlets of gold must have been deposited in a regular set of fractures whose origin is linked with stresses that affected the quartz after its consolidation. There is no reason to doubt that the gold is distinctly later than the quartz and that little or nothing was deposited with the metal. Fig. 1 gives a clear idea of this occurrence.[2]

[1] Hawley, J. E.: Riebeckite in quartz veins from the Michipicoten district, Ontario. Am. Mineral, vol. 22, pp. 1099–1108, 1937.

[2] Gunning, H. C.: Cadillac area, Quebec. Can. Geol. Surv., Mem. 206, pp. 49–54, 1937.

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*Siscoe.*—Twenty-five miles to the east of the O'Brien Cadillac is the Siscoe Gold mine. The country rocks of the deposit are granodiorite, greenstones, and, in minor amounts, dikes of albitite, diorite and syenite porphyry. Generally speaking the ore bodies can be classed into two main groups.

(*a*) Various vein systems, believed to be, in the majority of cases, tension openings filled with well fractured quartz with

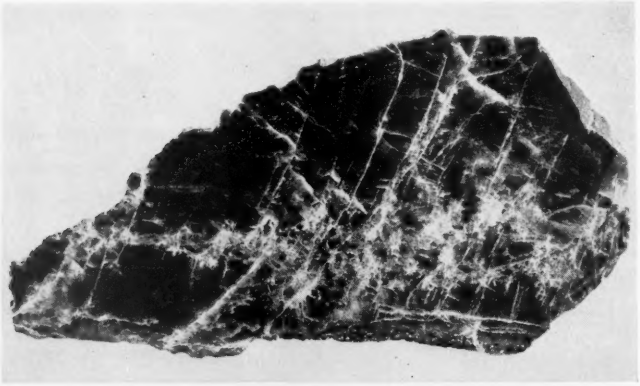

FIG. 1. Dark grey quartz veined by native gold. Light areas and lines in center and upper part of specimen largely gold. Small white crystals of arsenopyrite are visible along lower edge of specimen and some with gold in its central part. O'Brien Gold Mines, Limited, No. 4 vein. Natural size. Coloured reproduction of this specimen is the frontispiece in Memoir 206, Geological Survey, Canada. Reproduced by permission Bur. of Geol. & Top. Dept. of Mines and Res., Canada.

varying amounts of tourmaline, up to 75 per cent, and sparing amounts of sulphides; pyrrhotite apparently being rare or absent. Visible gold, in places, in spectacular amounts, is common and in some cases occurs along fractures in the quartz.

(*b*) K-Zone ore-bodies, which occur along a major fault. This strong shear and subordinate, related structures have been traced for several thousand feet in length and to as much as 1900

ft. in depth. The ore bodies in this zone are considered by Backman [3] to belong to three general types.

(1) Granular, white quartz containing two to three per cent of sulphides consisting of pyrite, chalcopyrite, and pyrrhotite. The quartz is fractured and banded with chlorite and in places contains fine visible gold.

(2) Mineralized talc-chlorite schist.

(3) Green talc containing visible gold.

A really remarkable specimen from this last type was shown to the writer by Dr. W. F. James. This is a mass of talc, a slickensided face of which is powdered and coated with gold. There is no evidence that anything was deposited with the gold; no quartz, tourmaline, or any of the above mentioned sulphides are present and the talc shows no obvious characteristics dissimilar to those of the other talc masses of the district. Here the evidence clearly points to the gold having no close relationship to the common vein materials, of which there are at least two main groups in the mine. Presuming that the main gold enrichment of this deposit occurred at one general time, which is altogether likely, it is far more logical to imagine its introduction later into the usual vein materials than to consider the gold was deposited first and the vein materials afterwards.

*Noranda.*—A gold deposit dissimilar from the preceding occurs in this part of Quebec, in the great Noranda copper-gold deposit. The original Keewatin lavas, breccias, and tuffs of this locality were intruded by what are now a highly altered quartz diorite (older gabbro), various later acid intrusives, and finally dikes of fresh diabase of late pre-Cambrian age. The sulphide bodies in the main are replacements of the acid Keewatin volcanics.[4] Their tenor in copper and gold vary and no constant quantitative relationship exists between the copper and gold, and that is ap-

[3] Backman, O. L.: Siscoe Gold Mine: A review. Can. Inst. Min. Met., no. 306, pp. 593–596, 1937.

[4] Cooke, James and Mawdsley: Geology and ore deposits of Rouyn-Harricanaw region, Que. Geo. Sur. Can., Mem. 166, pp. 183–206, 1931. Price, Peter: Geology and ore deposits of the Horne mine, Noranda, Que. Can. Inst. Min. Met., vol. 29, pp. 108–140, 1934. Suffel, G. G.: Relations of later gabbro to sulphides at the Horne mine, Noranda, Quebec. ECON. GEOL., vol. 30, pp. 905–915, 1935.

parently equally true with respect to the gold and the other introduced minerals. The generally accepted age of the heavy sulphide mineralization is that it is post-altered quartz diorite and pre-fresh diabase, and is the view most favoured by the writer. Nevertheless, the mine staff are largely of the opinion that the heavy sulphide mineralization is post-later diabase.

In discussing the question of late gold with Mr. Howard Butterfield, former geologist with the Noranda Company, he mentioned an interesting occurrence that had been forcibly brought to his attention by the routine sampling of the mine. An unusually high gold assay was reported from a channel sample taken in one of the later diabase dykes. On examining the place sampled, it was found that a pronounced slickensided slip in this dike was powdered with free gold. There was no connection in this case between the sulphides and the gold.

The lack of regularity of the gold content in the sulphide bodies is easily explainable on the assumption that gold was later introduced along channels open at that time. If one accepts the pre-fresh diabase age for the sulphides and believes that the major gold enrichment came at one time, one is forced to the conclusion that the gold was introduced not only later than the sulphides, but much later.

*Opemiska, Quebec.*

The Opemiska Copper Mines property, a copper-gold deposit, 200 miles northeast of Noranda, Quebec, and 25 miles south west of Lake Chibougamau, is an interesting occurrence. Ore bodies occur in what Dr. Duncan Derry has proved to be a large differentiated sill that has abrupt gradational contacts between rock types varying from peridotite to diorite.[5] The types of mineralization present in order of age from oldest to youngest are:

(*a*) Veins or dikes of magnetite;

(*b*) Quartz veins, usually with some pyrite;

(*c*) Chalcopyrite-pyrrhotite-rich veins which in some cases cement a breccia of an older quartz vein and in other cases do not contain any quartz at all; and

[5] Unpublished map.

(*d*) a quartz arsenopyrite vein which on Opemiska hill has a northwesterly strike and cuts and displaces the east-west copper-bearing bodies; arsenopyrite does not occur in the chalcopyrite-pyrrhotite bodies. Other metallic minerals such as pyrite, sphalerite, galena, and specularite are also present in this deposit. Gold is notable in the late arsenopyrite-rich vein and in some, but not all, of the copper-bearing veins.

The simplest explanation of the gold distribution in this deposit is that it was the last metal to be introduced; it followed fractures that reopened the late arsenopyrite vein and some of the earlier formed copper-bearing lodes.

### *Central Patricia Area, Ontario.*

The two producing gold mines in this area are the Central Patricia and the Pickle Crow, which lie about 125 miles northeast of Sioux Lookout. During the past summer, the writer studied in some detail the first deposit and the deposit at the Springer shaft, about 3½ miles east of the Central Patricia, and examined briefly other occurrences in this locality.

The general geology of the district is briefly as follows. Keewatin greenstones with interbedded bands of iron formation, in places cherty and low in iron, have been intensely deformed into steep to almost vertically plunging folds. This series or system has been intruded by granitic rocks including linear masses of feldspar porphyry. These latter bodies like some of the volcanics are intensely sheared. A few fresh diabase dikes cut across these rocks. Strong shear zones indicating pronounced movement are recognized throughout the region, especially in the vicinity or neighbouring the deposits of interest.[6]

Gold occurs in three distinct types of deposits in the district. (*a*) On the Central Patricia the ore bodies occur in the brittle iron formation, and consist of closely spaced cross fractures along which much pyrrhotite occurs with varying amounts of quartz. The pyrrhotite in many cases replaces the iron or chlorite-rich bands of the cherty iron formation for many inches from these

[6] Thomson, J. E.: Forthcoming report, Ont. Dept. Min.

veins. Small amounts of pyrite, arsenopyrite, and sphalerite also occur irregularly distributed through the deposit. The pyrrhotite of the wall rocks has definitely been deposited from solutions that worked out from the cross fractures since it progressively decreases in amount outward from them, and near the fractures has even replaced the chert bands. Samples taken of the pyrrhotite some distance from the fractures generally do not contain gold. Many sizeable quartz masses, mostly in the greenstones or at the contact of greenstone and banded iron formation, are also generally barren. There seems to be no close relationship between the gold content and the pyrrhotite, or the quartz. (*b*) The Springer vein consists of white, fractured quartz highly drag folded, low in sulphides, but containing free gold, in places in spectacular amounts. In some of the high grade ore, films of gold definitely traverse the quartz. The Pickle Crow mine, about 1½ miles northeast of the Springer contains a highly drag-folded gold-quartz vein, similar in mineralogical characteristics to the Springer. (*c*) About 1½ miles farther to the northeast the Albany mine discloses gold ore, which, from the writer's brief visit, appeared to be of three distinct types; one in iron formation with pyrrhotite, similar to that at the Central Patricia; another in quartz, similar to the Springer and the Pickle Crow; and good assays were reported from a highly contorted and mineralized schist apparently containing no quartz. Several instances were noted of free gold that traversed the quartz in a similar manner to that observed in the Springer deposit.

The veining of quartz by gold in the Albany, Springer, and Pickle Crow is taken by the writer clearly to indicate gold later than the formation of the quartz veins. The occurrence of gold ore, in this limited district, in three distinct types dissimilar in general character and also in relative mineral content strongly favors the argument that the gold mineralization has no close relationship to the other vein-forming materials. It is more reasonable to infer that the gold enrichment of these deposits occurred at one time. If this were the case it would be difficult to imagine that at this time the chemically susceptible gold was

in solution with varying proportions of the other vein-forming materials and thus bring about the three adjacent types of ore bodies noted. Again, it is more logical to consider the gold was introduced later, rather than prior to the associated vein matter. The functions of the brittle iron formation, quartz and schist can be considered as structural, affording an easy passage at the time of the introduction of the gold-bearing solutions. The various vein minerals would of course aid in its precipitation.

*Red Lake, Ontario.*

*Cochenour-Willans.*—The country rock of this deposit is highly altered, sheared, Keewatin greenstones and rhyolites largely replaced by iron-carbonate. Irregular veinlike masses of carbonate with varying amounts of quartz cut these rocks and were formed after the main period of shearing, but have since suffered mashing and dislocation. Later quartz of at least two ages also occurs. Narrow irregular dikes cut the above rocks with the possible exception of quartz of one age, since a few small veinlets of it cut the dikes. The original composition of these highly altered dike rocks is difficult to determine but they were probably close to a basic syenite in composition. Although completely altered, they are rarely sheared and, therefore, post-date most of the intense shearing suffered by the intruded rocks. A small amount of metallic minerals is irregularly distributed through this deposit and consists of pyrite, arsenopyrite, sphalerite, jamesonite (?), and free gold. They are generally confined to, or close to, the carbonate-quartz or quartz veins.

The arsenopyrite, possibly, and most, if not all of the pyrite are earlier than the dikes. The sphalerite and jamesonite are late and are present in veinlets that follow dike contacts. Gold occurs free in visible particles, commonly in spectacular amounts, and in places, although not everywhere, is associated with the above mentioned metallic minerals. In places the narrow dikes formed dams to the passage of the gold solutions; assays show that the gold ceases abruptly on one contact and is not present in the similar vein material on the other side of the dike.

That gold is much later than the main gangue minerals is clearly evident from the above. As might be expected, such details as films of gold traversing the fractured quartz, and rarely the carbonate, in the high grade sections are often evident. That the gold is not closely associated with the sphalerite and jamesonite is also evident, but their periods of deposition are not so widely separated as that of the gold and main gangue minerals. It has not been proved, but the writer suspects, that the gold was introduced later than these two minerals.

*Red Lake Gold Shore.*—The Red Lake Gold Shore mine is about 1 mile northwest of the Howey Mine near the centre of a highly fractured, and, in places, sheared and mashed granite mass.[7]

This granite contains, in the vicinity of the mine workings at least, numerous small inclusions of greenstones and altered equivalents, which are scattered through the mass and are present even in the lowest or 830-foot level. Various intermediate to fairly basic, narrow, altered, sheared dikes cut the granite. The ore is closely associated with one of them and is present in it and in the neighbouring granite. This ore consistently contains white to greyish, fractured quartz, either in large masses or in closely spaced, generally parallel, stringers. Sulphides are generally present both in the quartz and in the wall rock. Pyrite occurs as cubes and veinlets in the quartz. Chalcopyrite commonly veins the pyrite and is, therefore, later. The Ore Dressing Division of the Mines Branch, Ottawa, have determined, by microscopic examination, that these chalcopyrite veinlets in the pyrite commonly carry gold and some gangue. Some chalcopyrite in the mine does not carry gold and is, therefore, not closely related to it. In high grade sections of the ore bodies, films of gold traverse the fractured quartz. In places, it is in close association with irregular grains and films of a light grey, metallic mineral, which may be tennantite. This is also present without gold in similar fractures in the quartz. These two minerals were deposited later but pos-

[7] Hurst, M. E.: Gold deposits in the vicinity of Red Lake. Ont. Dept. Min., vol. 44, pt. 6, pp. 33–35, 1935.

sibly at slightly different times. The continuation of the quartz veins away from the ore shoots are commonly quite barren.

That gold has no close connection with the bulk of the vein forming material is quite evident and the final unravelling of the sequence of events may prove equally clearly here, as in the case of the Cochenour-Willans mine, that the gold enrichment of the deposit was much later than the formation of the bulk of the vein materials.

### CASES IN WHICH, PROBABLY, ONLY PART OF THE GOLD IS LATE.

Only two examples of this type will be discussed. Others, undoubtedly, exist and some discussed in the previous section might, on closer study, be found to belong in this group.

#### *Moneta, Porcupine District, Ontario.*

The gold vein on the Moneta property, just west of the Hollinger mine, lies along a steeply-dipping flow contact in part of which is a thin bed of fine tuff that has suffered pronounced movement and schisting. The vein is more or less typical of the carbonate-rich veins of this camp, quartz forming a small proportion of the lode. A study of hand specimens clearly shows veining, indicating at least two ages of the light-coloured, gangue minerals. Pyrite is practically the only sulphide present and forms about 20 per cent by weight of the ore.

Metallurgical tests carried out by the Ore Dressing Division of the Mines Branch, Ottawa, indicate that about 93 per cent of this gold can be recovered readily by cyanidation, but that about 7 per cent is so intimately associated with the pyrite that it cannot be recovered even when the sulphide concentrates are ground excessively fine and leached. This concentrate, after leaching, consistently contains a little less than 0.3 ounces of gold to the ton. Microphotographs of the ore show that the pyrite is excessively fractured and that the gold visible through the microscope occurs along these openings. That sub-microscopic gold occurs, is strongly suggested by the above metallurgical results. A series

of sulphur analyses was made to determine whether the gold content of the ore was directly proportional to its pyrite content; the results indicated that there is no close relationship between the pyrite and the gold.

In view of the evidence, it is reasonable to assume that appreciable gold is intimately associated with the ordinary pyrite of the deposit in sub-microscopic particles, apparently in definite proportion to it. Haycock [8] discusses the probable nature of such sub-microscopic gold associated with sulphides, but considers that at present it is premature to postulate that it occurs in either of the following states: in fine division, colloidal or solid solution. The microscopic evidence indicates that the balance of the gold is late. The sulphur-gold ratio tests which show no quantitative relationship between this gold and the pyrite also support this view.

A coarse pyrite not related to the above occurs sparsely in the mine.

Coarse gold, visible to the naked eye, is rare in this deposit but that found so far occurs with quartz-sphalerite-chalcopyrite veinlets that cut, and are later than, the main ore. This gold is, at least in part, intimately associated with the sulphides. It is still a question whether all of this late vein material was introduced at one time, or whether the gold was really later than the above quartz and sulphides; and, if later, whether it was introduced at the same time as the main gold enrichment of the deposit, the presence of the coarse visible gold being due to the physical and mineralogical characteristics of these veinlets. Close study would be necessary to determine this point.[9]

### *MacLeod-Cockshutt, Little Long Lac, Ontario.*

On this property an intrusive porphyry low in quartz fingers into fine sediments composed of dark arkose or greywacke, slate and some banded iron formation. Subsequent shearing and

[8] Haycock, M. H.: The role of the microscope in the study of gold ores. Can. Min. Met. Trans., vol. 11, pp. 405–414, 1937.

[9] Based on information supplied by W. E. Segsworth, President, J. D. Barrington, Manager, and W. F. James, Consulting Geologist.

other movements have affected all of these rocks.[10] Two general types of gold-bearing bodies are so far known. One is a recently discovered, highly contorted, white, fractured quartz vein, or folded saddle of considerable length and low pitch containing appreciable visible gold, but except for chlorite slips, a little tourmaline and a very little pyrite, nothing else of note. The other, typified by an important zone of considerable length and varying width, follows more or less closely one of the major porphyry-sediment contacts. This zone contains numerous quartz veins, much wall rock alteration (carbonate and disseminated pyrite), and lenses that are composed of as much as fifty to ninety per cent pyrite. Tourmaline, some of it late, chalcopyrite and arsenopyrite, are present in places. In quartz veins of possibly two ages, there are lens-shaped tension cracks healed with quartz and tourmaline. In this second type of gold-bearing bodies, the relative proportion of the disseminated pyrite is generally a good indication of the gold tenor of the ore. The lenses rich in pyrite, above referred to, vary notably in gold content; generally they assay an ounce or more to the ton, but others consistently carry about 0.03 ounces.[11]

It is most probable that in this mine with its two dissimilar types of ore, one without sulphides and one containing pyrite, the gold was introduced at the same time in both types. Further, the gold is probably late, except for that in the low grade pyrite lenses (.03 ozs. per ton), which was probably deposited at the time of the formation of the pyrite, and earlier than the main gold enrichment.

## INFERENCES.

1. That gold is, in places, late, and in other places demonstratably much later than the bulk or all the vein minerals with which it is associated, is clearly evident from the above examples.

2. A corollary of the above is that the present widely recognized practice of classifying all gold veins into high, intermediate,

[10] Bruce, E. L.: New developments in the Little Long Lac area. Ont. Dept. Min., vol. 45, pt. 2, pp. 118–123, 1936.

[11] Personal communication by W. Samuels, geologist for the Company.

and low temperature types on the basis of the other minerals present in the veins is unsound. If late gold is demonstratably present, it is quite likely that in many deposits it was deposited at a distinctly different temperature than all, or most of the associated vein material. In some cases the temperature at which it was deposited would be similar to that at which the gangue was deposited. In others it might be distinctly higher or lower.

A fuller knowledge of gold occurrences may show that the bulk of it was deposited within a more confined range of conditions than is now believed to be the case.

3. The general tendency for valuable gold ore to occur in shoots within a vein or vein system is in most cases explainable by assuming that it is later than the bulk of the vein materials and that its localization is due, to a great extent, on its following late channels. These channels would be openings formed by late stresses after the consolidation of the bulk of the vein.

The recognition of the presence or absence of these late-formed, strain features, is, therefore, of considerable economic importance. Their recognition nevertheless will not be easy in most cases, as the writer strongly suspects that they are mostly brought about by minor stresses. The materials most susceptable to such stresses would be the ones that are distinctly weak. The wide spread occurrence of gold-bearing ore shoots in quartz veins is explainable, assuming late gold, in that the brittle quartz fractured more easily than the neighbouring rocks, forming suitable channels for the passage of the gold-bearing solutions from depth.

The pronounced predilection of the Canadian prospector, based on keen observation and wide experience, for well fractured vein quartz, has, in view of the above, a sound basis.

## EXPLANATION OF THE OCCURRENCE OF LATE GOLD.

An attempt to explain this late deposition of gold meets many difficulties. In common with other geochemical problems, the direct evidence is scanty and the indirect is hard to evaluate. In spite of the difficulties, the problem is too interesting and important to neglect. There is no thought on the part of the writer

that the hypothesis here put forward is more than an attempted explanation, lacking a certain completeness and precision that must eventually be brought to it.

On first thought, it would be expected that such an insoluble substance as gold, far down on the electromotive series, should be the first to be precipitated from vein-forming solutions, rather than the last. That it should be later and commonly much later than the deposition of the common metal sulphides, for instance, is difficult to visualize. The mill or smelter superintendent will vouch for the difficulty of keeping gold in solution with even a trace of these other metals present in a system. It, therefore, seems wise to assume that, at least, much vein quartz and associated metallic minerals and many sulphide deposits have an immediate origin separate from that of gold, especially when the latter occurs in profitable concentration; but, of course, their ultimate origin is all magmatic. The question at once arises: "What process or mechanism would split these two magmatic substances apart?"

Fenner [12] has clearly indicated how this might be accomplished, though he does not specifically discuss the problem of late gold. This process has also been considered but is not favoured by Newhouse.[13] On sound physico-chemical grounds, he argues that, in the course of a metal-bearing magma advancing into a region of low pressure in the upper reaches of the earth's crust, the volatile substances could distill off. Bubbles could form and rise through the magma and compounds having a high vapour pressure, even though in low concentration, would distill into these bubbles and rise towards the surface. Undoubtedly, water vapour would be an abundant constituent and the relatively volatile compounds of the common metals, of which there are many, would also be collected and transported upwards towards the zones of fracture that are the ultimate locus of metal and quartz veins. On approaching this region, these substances would enter a zone

[12] Fenner, C. N.: Ore deposits of the western states. A. I. M. E., pp. 58–106, 1933.

[13] Newhouse, W. H.: The time sequence of hypogene ore mineral deposition. ECON. GEOL., vol. 23, pp. 647–659, 1928.

of lower temperature and the vapours would condense to liquids. The final deposition of these materials from solution would be in line with the evidence on the formation of metal veins.

The mineral deposits that are recognized as formed directly from vapours are exceedingly few and the evidence supporting liquid vein-forming solutions is very strong and generally accepted. There is no reason to believe that the gold-bearing veins are in any way an exception.

The presence of quartz, a substance with low volatility, commonly in abundance in such deposits, although of course there are numerous metallic sulphide deposits which contain little or none of it, is no argument against the process. Superheated water is, itself a powerful agent for the collection of silica from a silicious magma or rock. The passage of this later collected material into the veins or lodes in liquid solution is logical and is not opposed to the evidence.

During the course of the above postulated series of events, the relatively non-volatile gold has had no opportunity to join the vein-forming materials. It is conceived to be left behind in solution in the remaining magma. It is conceivable that the parent source was during a long interval of time, and possibly at various stages, impoverished of its volatile constituents, resulting in relative decrease in materials, like water, that could ultimately be liquid magmatic residues. The remaining ultimate liquid, under suitable conditions, would be relatively enriched in gold, possibly in alkalies, but singularly low in other metals. The time would then come, on the final consolidation of such a magma, that this residual liquid would be expelled. Gold in its few soluble compounds could then traverse fractures of later date than those traversed by the previously deposited quartz, metal compounds and other vein-forming minerals.

A serious objection that becomes apparent in connection with considering the gold as entering with a liquid end-differentiate, is the absence of valuable gold deposits with pegmatites, which are considered to have this origin. An argument in defence would be that gold, after all, is a very rare substance and if dis-

sipated through the great volume of pegmatite material, not uncommonly present with the related granitic masses, its concentration in any single pegmatite would be very small. Gold is known with pegmatites but their very method of formation does not favor its extreme concentration in a final residual liquid as postulated above.

The precipitation of gold by previously deposited minerals, such as the sulphides, containing elements with high electromotive properties, would be rapid. A possible reason why gold probably has not been recognized more often to be late, is that its opportunity to vein the previously deposited minerals (the criteria most often used) appears small. It would tend to precipitate as soon as it came in contact with such materials, and would be expected to coat the mineral grains, or to occur as mere blebs in contact with them. Quartz is probably more inert in this respect, and gold veining quartz may be a more common phenomena.

An explanation for the occurrences in which only part of the gold is late is that in these cases there was an intermingling of the first products of distillation from the magma with some of the late liquid end-differentiate containing gold. Only part of this differentiate, possibly, had collected or only a fraction joined the earlier mineralizers on their upward passage to the loci of final deposition. Such a liquid would be complex, and, as far as the gold is concerned, a remarkable state of equilibrium must have existed.

In cases where the deposition of the gold is demonstrably closely contemporaneous with that of the sulphides, analogous minerals and gangue, no inference can be made that they separated from the parent magma in different ways. They, of course, may have, but their final paths are the same and that is after all the only part we are acquainted with. In these cases also, it must be considered that the highly insoluble gold is in solution prior to deposition, in a chemical system in remarkably delicate equilibrium. The difficulty of imagining this set of conditions as existing in all cases is enough to make one favour some different sort of chemical mechanism for many of them, as outlined above and

strongly supported by the evidence of distinctly late gold in the deposits above cited.

### DEDUCTIONS FROM THE ABOVE HYPOTHESIS.

The hypothesis is believed to be in agreement with the evidence and its inferences above listed. From it, some further deductions can be made:

(1) In many cases, primary sulphides, not of the orthomagmatic type, were probably precipitated from liquid solutions originating from the condensation of vapour distillates from magma.

(2) It is altogether likely that whenever gold occurs in primary deposits, in spectacular amounts or in large commercial quantities, it was introduced distinctly late and may have its origin in liquid solutions derived directly from the magma residual after long crystallization.

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*January 10, 1937.*

# HISTORICAL BACKGROUND OF DOWNWARD SECONDARY ENRICHMENT THEORY.

J. S. BROWN.

ABSTRACT.

The author believes that the importance of the contribution made by practicing engineers to the formulation of the theory of secondary (supergene) enrichment is not generally appreciated, and reviews some of the published records from that viewpoint.

FORMULATION of the theory of downward secondary enrichment of metallic sulphide ores into an effective principle of economic geology is generally, and rightly, credited mainly to three men, whose papers setting forth their conclusions from years of observation all appeared in one distinguished volume of the Am. Inst. Min. Eng.[1] These men give appropriate credit to articles by Penrose,[2] De Launay[3] and others for stimulation in the formation of their theories, and also credit a number of mining engineers, such as Jas. Douglas, T. Sterry Hunt and A. F. Wendt with statements supporting their conclusions. Indeed, the observations of Hunt, Wendt, Olcott and others with respect to the famous black copper ores of the southern Appalachians are practically specific recognition of the theory but without broad generalization. It is my desire to review briefly the published opinions of these early observers in order to show how extensively the principle seems to have been recognized by practicing engineers before its popularization among the geological fraternity, and in particular to restore a measure of credit to

[1] Van Hise, C. R.: Some principles controlling the deposition of ores. Am. Inst. Min. Eng. Trans., vol. 30, pp. 27–177, 1901. Emmons, S. F.: The secondary enrichment of ore deposits. Idem, pp. 177–217. Weed, W. H.: The enrichment of gold and silver veins. Idem, pp. 424–448.

[2] Penrose, R. A. F.: The superficial alteration of ore deposits. Jour. Geol., vol. 2, pp. 288–317, 1894.

[3] De Launay, M. L.: Contributions a l'Etude des Gites Métallifères. Annales des Mines, 9th Se., vol. 12, 1897.

a pioneer named Clayton who seems to have been forgotten altogether by his successors.

In describing the Ore Knob, N. C., deposit Hunt [4] says:

> The curious phenomenon of the occurrence of the black ores in these deposits between the gossan above and the unchanged pyritous ores beneath has often been described, and there seems no good reason to question the received explanation that they owe their origin to the reduction, in some imperfectly explained way, of the sulphates formerly generated by oxidation in the upper portion of the lodes, which, as is well known, is changed into a porous mass of hydrous peroxide of iron holding more or less oxide and green carbonate of copper in its lower portions. Pyrrhotine, as I have found, is not without action on copper solutions, and its agency has been, with great probability, suggested by Prof. Henry Wurtz as accounting for the precipitation of a copper sulphide. . . .

Similarly Olcott [5] writes of the same deposit as follows:

> The character of the limonite affords quite certain information to the experienced eye of the quality of the underlying ore. As its porosity is indicative of the leaching away of much copper, it is likely that beneath open and porous gossan will be found good ore, while on the other hand compactness of limonite is an undesirable sign. . . .
>
> Next below the gossan is found the so-called black ore, which is an excellent copper mineral, yielding from 18 to 60 per cent of the metal. The black color of this ore is caused by the existence of copper glance, which is the result of the decomposition of copper pyrites. It is quite evident that the copper once contained in the gossan above has been leached out and re-deposited, causing a recomposition of the ores, now appearing of a black color. The depth of this black ore is about 30 feet, with an average width of 12 feet.
>
> When this is passed through the true or unaltered mineral of the vein is met. This is a chalcopyrite, nearly of the formula $Cu_2S.Fe_2S_3$, consequently containing about 34.6 per cent copper. Associated therewith is magnetite, pyrrhotite, pyrite, quartz, garnet, epidote, hornblende, black mica, calcite, prochlorite, besides the copper minerals. The ore in depth will average 7 per cent. . . .

The same conclusion was expressed more succinctly by Wendt [6] a few years later referring to Ducktown:

> Below the gossan and above the undecomposed yellow sulphurets, the copper that was originally contained in the croppings has been reprecipitated, forming the rich layers of "black ore," which first gave fame to the Ducktown mines, and which were worked many years ago by the Romans in Spain.

[4] Hunt, T. S.: The Ore Knob copper mine and some related deposits. Am. Inst. Min. Eng. Trans., vol. 2, pp. 123–129, 1875. See p. 127.

[5] Olcott, E. E.: Ore Knob copper mine and reduction works, Ashe County, N. C. Am. Inst. Min. Eng. Trans., vol. 3, pp. 391–399, 1875.

[6] Wendt, A. F.: The pyrites deposits of the Alleghanies. School of Mines Quarterly, vol. 7, pp. 154–188, 1885. See p. 160.

The allusion to Spain may well be amplified by a quotation from Becker,[7] reviewing this subject in retrospect.

> Secondary enrichment of sulphide ores attracted attention in Europe earlier than in this country. The relative affinity of the metals for sulphur was investigated as long ago as 1837, by E. F. Anthon [refers to Anthon and Schürmann], but the first application to ore deposits with which I have met is contained in Mr. Joaquin Gonzalos' admirable monograph on Huelva, issued in 1888. The secondary deposits of chalcopyrite (occasionally accompanied by other copper-compounds), and galena, as they are found at Rio Tinto, are described by the Spanish geologist as occurring along lithoclastic fractures in the mass of the pyrite. They are attributed to a process of segregation within the mass and to the reduction of sulphates percolating downward from the zone of oxidation [citation]. Mr. J. H. L. Vogt, after personal examination, entirely assented to Mr. Gonzalos' views, and pointed out subsequently that secondary enrichment is the true meaning of that old proverb: Es thut kein so gut, Er hat einen eisernen Hut [citation].

Becker also mentions the suggestions of James Douglas[8] with respect to Butte, which were as follows:

> The mines which lie at the extremities of the most productive section of the lode, viz.: the Gagnon and Original on the west and the Colusa on the east, are likewise lowest in level. In them, the copper-ore came to the surface, whereas in the Anaconda and Mountain View, which crown the hill several hundred feet above the terminal mines, the surface ores to a depth of four hundred feet carry some silver but no notable quantity of copper. At about that depth, however, great bodies of oxisulphurets and erubescite were met with in the Anaconda, from which, in the early days, ores running fifty per cent, and over, in copper were mined by tens of thousands of tons. Subsequently, the Mountain View commenced to yield from about the same depth the rich decomposed ores which are now assisting the large product of the Boston and Montana Company. The same oxisulphurets come to the surface, or are found near the surface, when the lode crops out in the valleys and on the flanks of the hill. But their depth and richness there are not as great as they are on the summit, where it seems as if the copper, leached out of the four hundred feet of depleted vein, had been concentrated in the underlying ore, and had thus produced a zone of secondary ore about two hundred feet deep, which contains, as might be expected, about thrice its normal copper content. In the decuprified surface-ore, silver was retained as an insoluble chloride when the soluble copper was removed. Therefore, we find that the proportion of silver to copper is less in the enriched copper zone, where an excess of copper is added to the normal silver contents, than in the unaltered ore beneath. . . .

There is one early exposition of this theory, however, which seems to have escaped the attention of the chief formulators of the

[7] Becker, G. F.: Biographical notice of Samuel Franklin Emmons. Am. Inst. Min. Eng. Trans., vol. 42, pp. 643–661, 1911. See pp. 652–653.

[8] Douglas, James: The copper resources of the United States. Am. Inst. Min. Eng. Trans., vol. 19, pp. 678–705, 1891. See p. 692.

theory and all subsequent reviewers, yet expresses its principle perhaps more clearly than any of the others. In describing the Atlanta, Idaho, gold-silver lode, Joshua E. Clayton [9] writes as follows:

> The metallic contents are gold, native silver, ruby silver, brittle silver ore and sulphide of silver. The brittle silver, or black antimonial silver, is the most abundant ore. Next in quantity and value is the ruby silver. The native silver and silver glance are found only in small quantities. The free gold constitutes from 20 to 40 per cent of the total value. The other minerals are iron pyrites in moderate quantities disseminated through the granular, friable quartz, and the granitic inclosures of the lode. I saw but little traces of copper, zinc, or lead. In fact, this lode carries the purest ores of silver that I have ever seen in any extensive mine.
>
> Much of the quartz in this lode is comparatively barren. The rich streak of black sulphuret and ruby ore varies in width from one foot to six or seven feet, and alongside of it is a zone of pay rock equally as wide that carries a good percentage of free gold with silver ore disseminated through it, making the pay streak from two to fifteen feet wide, and extending in length underground in the Monarch and Buffalo claims nearly two thousand feet on the course of the lode.
>
> No rich silver ore has ever been found on the surface outcrop of the lode; occasional bunches of rich gold-bearing quartz have been found, and the surface dirt along the entire length of outcrop contains free gold. I could not find any distinct traces of chloride of silver anywhere on the lode. The country rock is a very old granite, that does not carry chlorine, hence no chloride of silver has been found in the exposed portions of the lode. In fact the croppings appear to have been impoverished by oxidation and leaching out of nearly all the silver above the water line.
>
> The oxidation of the sulphuret of silver changes it to a sulphate, which is soluble in water. Where chlorine is present it becomes fixed as an insoluble chloride, but where it is not present the sulphate dissolves and goes out with the surface water, or else settles down in the lode to the water line and redeposits as a sulphide, or as native silver if the proper chemical reagents are present. This, I think, is the true explanation of the absence of rich silver ore in the croppings of the Atlanta Lode.
>
> It does not follow that the lode carries rich silver ore below the water line throughout its whole length. If it did, it would be a remarkable exception to the general rule. The probabilities are that there are a number of rich chimneys in the lode, with poor or even barren spaces between them; but as the rich silver ore does not come to the surface, the position of the rich ore bodies can only be ascertained by underground explorations. As a rule, however, those portions of the outcrop that carry the most free gold will be the richest in silver below the water line.

It was the discovery of this remarkable statement, in the course of professional work in the Atlanta district, which led me into the preceding inquiry, and caused me also to investigate

[9] Clayton, J. E.: Atlanta district. Am. Inst. Min. Eng. Trans., vol. 5, pp. 468–473, 1877.

in some detail the published record of the author. From this I infer that his ideas regarding secondary enrichment originated in a personal acquaintance with the Southern Appalachian copper district for Hunt, in his article on Ore Knob (p. 123), mentions that the deposit had just been reopened "by S. S. and J. E. Clayton of Baltimore," and Olcott (p. 391) states that:

> The works of the Ore Knob Copper Company have been energetically pushed forward, since the reopening of the mine, in the spring of 1873, by Mr. J. E. Clayton, the superintendent and one of the chief owners of the property, . . . .

Presumably this is the same Joshua E. Clayton.[10]

No additions have been found to the list of nine short articles credited to Clayton in the U. S. Geological Survey bibliography. Perusal of all of those dealing with ore deposits yields no further light on his theory as to secondary enrichment. The article on the Drumlummon mine,[11] however, well merits reading by one who may feel that the current theory of magmatic origin of ore deposits is wholly an invention of our recent contemporaries. I quote only one suggestive sentence:

> According to this theory of the mineralization of great "true fissures" the conditions precedent are: First, a fissure deep enough to tap the heated zone of the earth's crust; second, a shifting of the walls sufficiently to leave openings for the escape of hot gas and mineralized hot solutions up through them.

In conclusion I wish to express my appreciation to Prof. H. Ries for his friendly interest in the preparation of this article.

EDWARDS, N. Y.,
*Nov. 17, 1937.*

[10] Clayton's death is recorded in the Engineering and Mining Journal, vol. 48, p. 121, 1889. He was born in Georgia in 1820 and died at Wardour Jct., Idaho, on July 3, 1889, of blood poison resulting from a stagecoach accident. The same volume, pp. 90–91, carries a warm editorial tribute by R. W. Raymond, and on page 251 under "personals" is this statement:

"It is suggested that a monument to the late Professor Joshua E. Clayton . . . be erected by the miners of Montana, Utah, Colorado, and the Coeur d'Alene district, where his work has been of such inestimable value."

In several places he is referred to as "Professor," but I find no information as to where he taught, or what, if at all. Records of the Am. Inst. Min. Eng. show him elected to membership in 1874, his address for several succeeding years being Salt Lake, Utah, and thereafter, Portland, Ore.

[11] Clayton, Joshua E.: The Drumlummon group of veins and their mode of formation. Eng. & Min. Jour., vol. 46, pp. 85–86; pp. 106–108, 1888.

# DISCUSSION AND COMMUNICATIONS

## *THE ORIGIN OF PRIMARY LEAD ORES.*

*Sir:*—The recent paper on lead ores by Professor Arthur Holmes [1] is very interesting, as is his book on the age of the earth, but its chief value seems to lie in its presentation of certain fundamental information rather than in the conclusions.

Nothing is said about the concentration or derivation of lead from *sedimentary* rocks, which is still a possible theory for the derivation of lead ores. Presumably such lead must have come from other rocks at the time the sediments were formed. How old that lead might be it is difficult to say; it might be *cyclic* lead that had passed through sediments, been melted into igneous rocks and again gone into sediments, perhaps more than once, and it might have become contaminated with radiogenic lead at some stage in its course.

If radiogenic lead could have an atomic weight of about 207.21, that is, the same as common lead, the change in atomic weight of ore-lead with time would probably be too small to be detected. But Holmes assumes a lower atomic weight for radiogenic lead and the inquiry may be followed on that assumption.

The most striking feature in the problem, apparently, is not that the atomic weight of ore-lead does not vary with its geologic age, but that its atomic weight is quite different from that of "rock-lead." This feature may be accounted for equally well by assuming that radiogenic lead remains fixed in the uranium-thorium minerals and is not extracted by migrating waters to form ore deposits. If only common lead is so extracted and concentrated the lead of all ore deposits should be common lead, as appears to be the case. Some difference in the solubility of the minerals

[1] Holmes, Arthur: The origin of primary lead ores. ECON. GEOL., vol. 32, no. 6, p. 763, 1937.

might account for this difference in behavior. Such a behavior would also be of considerable help to those who seek to estimate geologic time from lead-uranium ratios, as it would give some additional assurance that the radiogenic lead tends to remain fixed near its parent elements.

An ore deposit may represent a redeposition of some previous concentration. In this way the origin of the lead would be pushed back to an earlier rock. Even if the original source had been an igneous rock the lead would probably have been extracted by a hydrothermal solution and it would still be possible for the radiogenic lead to remain fixed. Nothing short of a drastic treatment, such as fusion or solution in acid, might be able to extract the radiogenic lead. Can it be assumed from the evidence, however, that ore-lead has come from depths below the inferred granite and basalt levels?

With reference to Holmes' Fig. 3 it may be noted that, if the Paleozoic era is assumed to have begun 500 million years ago, the atomic weight of granitic rock-lead of early Paleozoic age would be 207.16, which is not very different from 207.14, the atomic weight of rock-lead in recent rocks. So small a difference could be revealed only by very careful determinations of the atomic weights, if the lead were anywhere available; hence the detection of any difference between granitic rock-lead of Mesozoic age and modern rock-lead would seem to be out of the question. Similarly, the difference for basaltic rock-lead would be only 0.03 from the beginning of Paleozoic time to the present. The situation might be more favorable of course for lead that originated in early pre-Cambrian time, provided that no radioactive elements accompanied the lead into the ore deposit, so that the ore would register the rock-lead of that particular time only. There seem to be a good many "ifs" in the problem. Still it might be worth while to make some further atomic weight determinations of the oldest ore-lead obtainable, with particular emphasis on any evidence tending to show that the ore was actually separated at the early time assumed.

ROGER C. WELLS.

U. S. GEOLOGICAL SURVEY,
*Dec. 20, 1937.*

## PARAGENESIS OF PYRRHOTITE.

*Sir:* In his paper upon "The Paragenesis of Pyrrhotite," published in the January–February 1937 issue of ECONOMIC GEOLOGY, G. M. Schwarz makes the following statements (p. 31):

> It (pyrrhotite) . . . is considered a definite evidence of high temperature of formation.
>
> The occurrence of pyrrhotite as an important mineral in ores is mainly limited to deposits classified as magmatic segregation, contact metamorphism and veins of the deep zone by Emmons, and as magmatic, pyrometasomatic and hypothermal by Lindgren.
>
> It is significant that the great amount of detailed microscopic work on polished ores since 1910 has verified the restriction of pyrrhotite to these deposits. In thousands of specimens from other types of deposits the writer has rarely seen even microscopic occurrences of pyrrhotite, and a review of the literature suggests that this is the experience of other investigators. Although pyrrhotite is found in several gold deposits classified as mesothermal, it is mostly small in amount, and the deposits are probably on the borderline between hypothermal and mesothermal zones.

Professor Schwarz has done a great deal of microscope work upon thin and polished sections, and as a consequence thereof has given to geologic literature a number of contributions of value. It is unfortunate that his field investigations have been less comprehensive, and that his lack of field observation in many districts should have led him, in connection with the recent paper, into making generalisations that are supported neither by sound logic nor by field facts that have been established by others. His implication that where pyrrhotite exists in deposits not of the high temperature type is occurs in insignificant amounts, and therefore may be ruled from consideration, is unscientific, particularly as he presents no data to establish, quantitatively, the percentage of material comprised by the pyrrhotite in any of the deposits noted. The writer has not available in Australia his field notes covering many of his North American observations regarding occurrence of pyrrhotite, but in the present instance it is not essential, since the citing of one well-defined occurrence of abundant pyrrhotite deposition under low temperature conditions

will suffice to compel vital modification of Professor Schwarz' thesis.

At Mount Isa, pyrrhotite is an abundant and general constituent of the orebodies, which occur within lenticular shear zones in shale. The nearest intrusive of any kind is a pegmatite dike two miles distant at the surface, which has broken intermittently through a body of hornblende schist. The nearest intrusive rock representing an important part of a magma (disregarding pre-ore gneissic-granite and the pre-ore diorite-hornblende-schist) is a granite batholith upward of 8 miles distant at the surface. No intrusive rock has been encountered underground to a depth of more than 900 ft., nor in extensive diamond drilling to depths of more than 1,400 ft. On basis of the regional geology it would be difficult to place the deposit lower than the upper or middle range of Graton's leptothermal zone.

Minerals of the orebodies that were deposited during the main period of ore deposition—when all of the pyrrhotite now known was introduced—are, in order of their sequence: arsenopyrite, pyrite, graphite, quartz and silicates; carbonate, an uncommon undetermined mineral, sphalerite, pyrrhotite, tetrahedrite, chalcopyrite, marcasite, and galena—with a certain degree of overlapping and recurrences of mineralization.[1]

Normal gangue of the sphalerite and pyrrhotite consists of shale locally altered to crystalline silicates—mainly chlorite, especially pennanite, with minor mica and zoisite—together with carbonate as dolomite and lesser ankerite.[1] Although Grondijs and Schouten have not mentioned it in their microscope study of the ore, field evidence shows that carbonate deposition as dolomite and ankerite continued during the introduction of the pyrrhotite and persisted to the end of the pyrrhotite deposition.[2]

As to the graphite being regarded as evidence of high temperature deposition at Mount Isa, Grondijs and Schouten state:

> Graphite is generally taken to be formed at rather high temperature and pressure, in pegmatitic-pneumatolytic ores or in contact metamorphic deposits. The presence of graphite in the Mount Isa ore is therefore of interest . . . because it has probably been formed at no high temperature.[1]

They adduce abundant evidence to prove the absence of high temperature in connection with the graphite occurrences.

The chalcopyrite at Mount Isa is too limited in amount and too scattered in its distribution to be an important ore constituent, but if proof were needed of its deposition under low temperature conditions that proof would lie in the fact that most of the chalcopyrite occurs within massive bodies, up to 200 ft. thick, of essentially pure hypogene dolomite-ankerite, and much of it shows co-deposition with those carbonates.

Further, to substantiate his contention that pyrrhotite is a high temperature mineral in the districts tabulated by him, Professor Schwarz states (p. 46): "Pyrrhotite commonly occurs without visible pentlandite, but pentlandite is rarely, if ever, found without pyrrhotite." An interesting and useful observation, but it proves nothing for his case, except that in 16 of the 86 instances tabulated by him, high temperatures may have prevailed during deposition of the pyrrhotite.

He is, however, merely arguing in a circle, for at Mount Isa pentlandite, although present in the ore only in small amount, was deposited under low temperature conditions, since it occurs associated intimately with the chalcopyrite which was so deposited.

That pyrrhotite at Mount Isa was deposited under these low temperature conditions in an orderly and not in a freak manner, is attested by Grondijs and Schouten's statement that (p. 425) "pyrrhotite grains 5 mm. long are not exceptional." Microphotographic evidence is furnished by them to establish the point.

Here, then, at Mount Isa is a clear-cut example of abundant pyrrhotite having been deposited under low temperature conditions in association with much lesser, but none the less noteworthy, amounts of graphite, chalcopyrite and pentlandite—which likewise were so plainly deposited under low temperature conditions that by no stretch of the imagination or distortion of the facts can their presence be used as evidence of high temperature conditions having prevailed during the pyrrhotite's introduction.

It may be of interest in that connection to present quantitative evidence regarding occurrence of pyrrhotite in the Mount Isa ore.

At Mount Isa the ore occurs mainly as thin bands, from 1/100 to ½ in. thick, of iron sulphides and of an intimate fine grained intermixture of galena and sphalerite,[3] these bands alternating with ones of barren shale equal or greater in thickness, so that the ore presents a ribboned appearance. Replacement of the shale by sulphides began along bedding planes and advanced irregularly, in places completely, through a given shale bed. To an important extent the galena and sphalerite replaced the iron sulphides, particularly the pyrite, but throughout the deposits pyrrhotite is plainly visible to the unaided eye, and in some portions of the largest (Black Star) oreshoot bands of practically pure pyrrhotite are present in thicknesses up to ⅛ in. and as blebs up to ½ in. across. Extensive microscope investigation has resulted in the pyrrhotite being estimated at not less than several per cent of the ore's content, and average analyses of the mill heads over the two year period during which the Mount Isa concentrator has operated on an all-sulphide basis shows 15.85 per cent of the mill feed to consist of iron sulphide, of which nearly 15 per cent in turn, or 2.35 per cent of the ore as milled, comprises pyrrhotite.

Mount Isa's June 30, 1937, combined ore production and reserves, in round figures, stood at 18,500,000 tons (calculated as short tons), containing, on basis of the data above presented, 434,750 tons of pyrrhotite.

That figure, however, does not represent total pyrrhotite present at Mount Isa. Deepest drillholes show no diminution in grade of the ore, no essential change in mineralogical content, and exhibit no mineralogical evidence for thinking that the ore will not persist to appreciably greater depth. Furthermore, the 18,500,000 tons embraces only ore regarded as commercial. Diamond drilling and underground exploratory work disclose probably an equal tonnage of mineralized rock occurring homogeneously associated with the commercial ore, but with lead con-

[3] In this paper the Mount Isa zinc, sulphide, for convenience, is referred to as sphalerite. Actually it carries isomorphously, on average, .075 per cent Fe to each 1 per cent Zn., as proved by numerous analyses of the purer zinc sulphide made during the past 6 years.

tent too low for economic extraction. Most of this lower grade material, incidentally, carries a proportionately higher content of pyrite and pyrrhotite than does the stoping ore—some of it, such as the "Pyrite Rib," which constitutes the hangingwall of the Black Star lode, possessing bands several feet thick of nearly massive pyrite—pyrrhotite, of which pyrrhotite constitutes upward of one quarter of the total volume. In pyrrhotite content the submarginal ore therefore contains a tonnage little, if any, below that of the commercial oreshoots. Allowing for pyrrhotite present in the submarginal ore, it consequently is in order to assume that the Mount Isa deposits, down to 1,400 ft. depth, contain not less than 850,000 tons of pyrrhotite. If any allowance be made for persistence of ore below the deepest drillholes, the tonnage of pyrrhotite in the district cannot well be conceived of as less than 1,000,000. All of it, or at least the 850,000 tons of which detailed knowldege is available, deposited under determined low temperature conditions, and all contained within a block of ground occupying a surface area 6,000 by 1,000 $\pm$ feet!

That is the evidence at Mount Isa. From the writer's observations in numerous other districts, he would say that the main difference between many of those deposits and the one at Mount Isa is that at the latter place the routine geological work has been supplemented by accurate day to day underground observation, and with sufficient chemical analyses and microscope work, to establish the pyrrhotite content quantitatively; *i.e.*, as a definite percentage of the ore. The failure of this to be done, or to be stated in the literature, for other districts does not authorize Professor Schwarz to assume that the pyrrhotite in those districts necessarily is insignificant in amount, particularly when the few microscope slides or sections available to him for study represent, at best, only a fraction of the millionth part of the orebodies under consideration, with no assurance that the material represented by the slides or sections has been selected with regard for disclosing either the abundance or percentage of pyrrhotite present.

Were the above quantitative information as to pyrrhotite content at Mount Isa not presented, and were Professor Schwarz seeking confirmation for his thesis in the paper recently published

by Grondijs and Schouten, it seems in order to assume, in view of the method employed elsewhere in his paper, that he would dismiss Mount Isa as one of the districts where only insignificant amounts of pyrrhotite exist, despite the fact that a million tons, more or less, of that mineral are known to have been deposited there under low temperature conditions.

In that connection one wonders whether his statement that "although pyrrhotite is found in several gold deposits classified as mesothermal, it is mostly small in amount, and the deposits are probably on the borderline between hypothermal and mesothermal zones" is based upon critical analysis of all available data and upon the maintenance of a judicial attitude toward points upon which full evidence is not at hand, or whether it merely expresses a casual generalization.

Attention might be directed to the "evidence" that chalcopyrite is a high temperature mineral (p. 43):

> Chalcopyrite is an almost universal associate of pyrrhotite as is shown by the fact that it was reported in all but 7 of the 86 deposits tabulated, and it is possible that detailed microscopic study of polished surfaces would reveal chalcopyrite where it has not been recorded.

The fact that both pyrrhotite and chalcopyrite are associated in numerous high temperature deposits in no sense establishes them or their association as irrefutable evidence of high temperature deposition. The testimony from Mount Isa proves that. Were the writer's field notes regarding several of the Red Bed copper deposits of southwestern United States at hand, further testimony to that effect would be forthcoming. Pyrite also occurs commonly and mostly in association with chalcopyrite. Does that establish pyrite as necessarily a high temperature mineral?

Professor Schwarz has made an assumption, then used that assumption as evidence to establish a case. By the rules of logic his conclusion must be invalid, and must itself constitute an assumption, even if his first premise were true—which it is not. Yet, unless challenged, such deductions continue to stand in geologic literature as the product of scientifically reasoned thought.

That Professor Schwarz has not studied carefully some of the data presented in his paper is shown by his statements under "Bornite" (p. 50), where he refers to a general antipathy between the association of pyrrhotite and bornite without attempting to explain the cause. His statement is ". . . the reason for the antipathy is not evident."

A glance at Figs. 1 and 2 of the Merwin-Lombard diagram [4] shows that under normal conditions anything but antipathy could not exist. In the absence of a knowledge of that diagram, the antipathy would be indicated by consideration of the molecular relationships that exist between chalcocite ($Cu_2S$), bornite ($2Cu_2S \cdot CuS \cdot FeS$), chalcopyrite ($CuS \cdot FeS$), cubanite ($CuS \cdot 2FeS$) and pyrrhotite ($FeS$).

Again, after referring to the common association of pyrrhotite with pyrite, he speaks (p. 33) of their "puzzling occurrence" together.

There is nothing puzzling about it. They occur in common association because both may be and commonly are deposited under high, low, and intermediate temperature conditions; although, with conditions otherwise equal and favorable to their respective precipitations, pyrite will crystallize out under conditions of somewhat lower temperature than will pyrrhotite. Those who have stood upon the crater rim of an active volcano and become suddenly enveloped by dense clouds of sulphur fumes, would ascribe, as the primary determining factor in the respective precipitation of pyrite and pyrrhotite, variability in their S and Fe content, and properly would assign to temperature, and to the related pressure phases, secondary roles.

No doubt in many schools of geologic teaching, pyrrhotite has been accepted unquestionably as "evidence" of high temperature deposition, based upon its common occurrence under such conditions, and upon the fact that in our eariler geologic literature broad generalizations, of which this is one, were advanced by outstanding men upon the acknowledged basis of limited observation, but in the hope of evolving comprehensible working hypotheses and lines of attack for the further study of ore deposition. Today, one may properly ask whether the time has not

arrived for a more critical appraisal of those generalizations in the light of knowledge added during the past 25 or 30 years. The Buddhist, Brahman, Mohammedan, and most sects of the Christian religion, have long relied upon the method of repetition to clothe their statements with authority, and modern advertisers, particularly in America, have developed it into a highly specialized art of misleading impressionism which they have learned from experience induces in the multitude, blind, unswerving conviction. But we prefer to think that science is more critical.

One reads almost any of the technical journals dealing with chemistry, physics, or the other sciences including even medicine, and is at once impressed with the clear recital of evidence for and against the case which the investigation has disclosed, and with the carefully guarded reasoning with which the conclusions are drawn.

Much of our geological literature, unfortunately, presents a sad contrast to that practice. Geology, admittedly, is the least exact of the sciences. But ought not that in itself to make us more, rather than less, critical in the analysis of our data and cautious in the basis of our deductions, and ought it not to constrain us to keep always prominently in the forefront the degree of doubt involved in conclusions based upon what most of us acknowledge can be, at best, only partial evidence?

ROLAND BLANCHARD.

MOUNT ISA MINES LIMITED,
MOUNT ISA, QUEENSLAND,
*October 1, 1937.*

[1] Grondijs, H. F., and Schouten, C.: A study of the Mount Isa ores. ECON. GEOL., vol. 32, no. 4, 1937.

[2] Blanchard, Roland and Hall, Graham: Notes on Mount Isa ore deposition. To be published in ECON. GEOL.

[4] Merwin, H. E., and Lombard, R. H.: The System Cu-Fe-S. ECON. GEOL., vol. 32, Supplement to No. 2, p. 206 and 216, 1937.

# REVIEWS

**Recent New York State Survey Reports.** (1) D. GALLAGHER: **Origin of the magnetite deposits at Lyon Mountain.** N. Y. State Mus. Bull. No. 311, pp. 85, figs. 17 (1937). (2) MEDORA H. KRIEGER: **Geology of the Thirteenth Lake quadrangle.** N. Y. State Mus. Bull. No. 308, pp. 124, figs. 31, 1 colored map, and 2 structure maps (1937). (3) A. F. BUDDINGTON: **Geology of the Santa Clara quadrangle.** N. Y. State Mus. Bull. No. 309, pp. 56, figs. 6, 1 colored map (1937). (4) R. S. CANNON: **Geology of the Piseco Lake quadrangle.** N. Y. State Mus. Bull. No. 312, pp. 107, figs. 17, 1 colored map, and 2 structure maps (1937).

The above bulletins are noteworthy contributions to Adirondack geology. Important mineral deposits are discussed in the first two reports, and the complicated structural problems of the intrusive rocks of the Adirondacks have been materially advanced by the structure maps that accompany nos. 2 and 4. Space is too limited to review the many interesting observations on the geomorphology of the Adirondacks, contained in the second, third, and fourth report. There can be little doubt that the increased attention to the structural details of the rocks proves of great value in the elucidation of economic, regional-geologic, and morphologic problems.

(1) This is a careful petrologic investigation of the well-known iron mining district in the northern Adirondacks, In the petrographically variable granitic gneiss which is the principal bedrock, the miners have encountered about 100 miarolitic cavities; "some are big enough for a man to crawl into with ease." When drilled, a gush of compressed water may spout 40 feet out of the drill hole. From the coarseness of the crystals inside the cavities, and from the scarcity of hydrothermal minerals it is concluded that the caves were filled by gases that developed in the mobile magma, like bubbles, during a late stage of the consolidation. The gneissic foliation was in existence before this stage, as is also proven by pegmatites that cross the foliation, or merge into coarse granite.

The principal magnetite bodies are lined up along a zone, 5 miles long from S.W. to N.E., dipping at intermediate angles west or northwest, conformably with the foliation of the granite. The tabular ore bodies attain thicknesses between 20 and 40 feet, and about 10 million tons of magnetite have been produced here since 1871. In addition to the com-

mercially important "massive" ore bodies, leaner ore is disseminated through the entire terrane of granite gneiss, but this has not been studied in detail.

The mineralization of the "massive" ore bodies is held to be due to pneumatolytic metasomatism, following closely the development of the pegmatites. The normal minerals of the granite have all been replaced by magnetite, and from the variations of mineral proportions, and from common albite rims around magnetite grains the author concludes that an unknown, but probably small, amount of albite was introduced immediately before magnetite. In the later pneumatolytic stage, however, magnetite far outdistanced all other minerals. The development of the gneissic foliation, the miarolitic cavities, and the magnetitization occurred at so nearly the same period that the bulk of the mineral assemblage was probably introduced at high temperatures. There is evidence of two stages of crystallization of magnetite: one very early during the consolidation of the granite, producing a few idiomorphic grains, and the other during the closing pneumatolytic stage, producing the ore bodies of anhedral magnetite. The concentration of iron oxide during the close of magma crystallization, postulated by Fenner, seems to hold true for Lyon Mountain, because both pegmatites and mineralizing agencies were probably derived from the same magma as the surrounding gneissic granite. The reviewer, having recently seen fine examples of cross-cutting ilmenite dikes, with or without coarse plagioclase (probably andesine) and pyroxene, in the anorthosite area of Egersund, Norway, would venture to suggest that a corresponding repetition of crystallization may occur, for ilmenite, in anorthosite masses.

A composite block diagram helps to illustrate the structures of the rocks, complicated by dikes and some faults. Excellent photomicrographs, tables of mineral composition, and a bibliography accompany the report.

(2) The Thirteenth Lake region is a rugged mountain group, some 20 miles south of the high anorthosite mountains. To map such an inaccessible area in detail is in itself no small achievement. The geology of this region is of special interest for in it lies the famous Barton garnet mine, and the only large outlier of anorthosite, outside the main mass farther north.

The subcircular anorthosite mass crops out over some 90 square miles, most of it in the central and southwestern portions of the quadrangle. It is surrounded by syenitic and granitic gneisses among which several spherical gabbros are scattered, up to 1½ miles in diameter. This association of rocks is typical of many other districts in the Adirondacks. The massive core of anorthosite passes outwardly into foliated "Whiteface" anorthosite, and the dips indicate a domical surface. On this dome, the syenitic gneisses seem to repose, although the eastern border of the

anorthosite is perhaps underlain by syenite. The consanguineous relation between the three intrusive rocks is indicated by common interlayering of these rocks (p. 35, 36, 53), and by xenocrysts of labradorite in both gabbro and syenite, as far as 3½ miles from the nearest anorthosite outcrops (p. 56).

Of the 11 noteworthy concentrations of garnet in the area, the one at the Barton mine is the most remarkable. Garnets occur as single crystals, averaging 3 to 8 inches, but locally attaining maximum diameters of 3 feet. They are surrounded by hornblende shells. The rock between the crystals is a diorite with andesine, hornblende, and other ferromagnesians. The deposit is thought to be a flat lens, dipping gently to the west. The top is interbedded with gabbro, the narrow east and west terminations border against anorthosite, and the steep southern border appears to truncate syenite, although it is held that the crystals antedate the emplacement of the syenite. The origin of the deposit is still open to several interpretations. It may be an unusually recrystallized lens of Grenville sediments, or a mass of gabbro, recrystallized under peculiar conditions. Other, leaner, concentrations of garnet are associated with more acidic gneisses; their origin has not been studied.

(3) The Santa Clara quadrangle lies along the northern border of the pre-Cambrian rocks of the Adirondacks, south of Malone, N. Y., and but a few miles south of the Paleozoic cover. The principal bedrock is the Santa Clara complex of syenitic and quartz-syenitic gneisses. Lenses and sills of metagabbro are older, and the St. Regis granite is younger. Diabase dikes occur in the north, and Grenville sediments are absent.

Concerning the emplacement of the igneous suite, the author submits the following hypothesis. The gabbroic rocks were intruded concordantly into flat-lying Grenville sediments. Then followed the intrusion of the Santa Clara complex, also as subhorizontal masses. They are held to have differentiated by gravity into a heavy quartz-pyroxene syenite (sp. gr. 2.68–2.72), and a light biotite granite (sp. gr. 2.623–2.710). Following their emplacement, "strong deformative forces of orogenic . . . intensity acted across this region" (p. 9), and folded all rocks. Probably late during this orogeny, the St. Regis granite was intruded, cross-cutting locally older structures. The author concedes that this is a tentative theory "that must be tested over a wider area" (p. 10). To the reviewer, the arguments as advanced here seem, indeed, in need of considerable additional investigation. In particular the relation between the granulation of the syenitic gneisses and their associated pegmatites should receive further study. In all gneissic intrusives in the eastern Adirondacks with which the reviewer is familiar, the degree of granulation varies in intensity, and is almost everywhere older than the pegmatitic stringers. This is commonly regarded as a strong argument for the early age of

the granulation, in the sense that it antedates the last stage of consolidation. Although the author states (p. 49) that even diabase dikes are foliated across their contacts in an adjoining quadrangle, only one locality is given at which pegmatites are also deformed, whereas at other localities (p. 50) pegmatites are not crushed but the syenite is. The supposed independence of syenite intrusion and later folding hinges on this relationship. The difference in specific gravity between the syenite varieties and granite seems small to support the theory of gravity differentiation effectively, and in the absence of clearly identifiable Grenville rocks, it is difficult to prove that the medium-grained pyroxene-hornblende quartz syenite, which surrounds outwardly much of the Santa Clara complex, is the original chill facies of the complex (p. 43). How could the same rock that was chilled along its original contact, at the same time "assimilate" the surrounding (older) metagabbro (p. 43)? The assumed cross-cutting nature of the St. Regis granite needs qualification. It is true that its mapped contacts appear to cross-cut, locally, the foliation of the older syenitic gneisses; but as the actual contacts are nowhere exposed, it is still possible that the later rock bends through flexures into conformable contacts.

Although not all aspects of Buddington's theory can be said to have adequate support in the field observations available at present, the gist of the new hypothesis will no doubt exert a strong and healthy stimulus on further structural work in the Adirondacks.

(4) The Piseco Lake quadrangle lies some 60 miles southwest of the Adirondack anorthosite, and about 35 miles southwest of the Thirteenth Lake area. The object of the survey was to combine structural and petrologic methods in the detailed study of the large Piseco gneiss dome that covers the northern half of the quadrangle. The report is without doubt the most painstaking compilation of structural data in any single area of the Adirondacks, and the two structure maps reveal an extraordinary amount of field work. This report sets a new standard for structural mapping in the Adirondacks.

A series of Grenville garnet gneisses, quartzites, and quartz-diopside rocks has here been intruded by metagabbro, anorthosite-norite, two varieties of quartz syenite, and granite. The anorthosite-gabbro-norite suite occurs only in one small syncline along the eastern border, but is interesting as this represents the southwesternmost outcrop of anorthosite known.

In the southern half of the area, the mixed syenite and Grenville gneisses dip southward at gentle or intermediate angles, and rest, on the north, on the Piseco dome, which trends east-west with an axis 10 miles long, and a width of about 5 miles. Its core and a crescent-shaped mass to the west of it are composed of granite, whereas syenitic gneisses constitute

the intermediate and peripheral belts. The author assumes as does Buddington, that the syenite bodies consolidated as sills in flat-lying Grenville strata, and that a subsequent period of mountain building caused the intrusion of the later granite. The latter formed phacoliths at the crests of folds, thickening at apical zones.

In the syenitic gneisses an early, primary, and a secondary, later foliation are distinguished. The reviewer doubts the wisdom of this terminology. In contrast to the first foliation, which is the parallel orientation of lenses or layers of compositionally contrasting syenite types, or amphibolite, the secondary foliation is said to be everywhere parallel to the early one, and consists of "flattened lenticles of granulated feldspar, thin sheets of granulated mafic minerals, and platy crystalloblastic mineral individuals, especially leaves of quartz and flakes of biotite" (p. 50). The two are difficult to distinguish in many cases (p. 51), and the later structure overlaps (p. 50, 59) or precedes the consolidation of pegmatites (p. 59). To the reviewer the evidence seems inadequate that an appreciable hiatus should separate the intrusion of the syenite sills and the supposed orogenic movements that granulated and deformed the intrusions. As an alternative he would suggest that the deformation of the syenitic rocks is predominantly precrystalline, and to a small extent para- and postcrystalline, but essentially synchronous with the syenite intrusion. Broken crystal individuals, and elongation of mineral clusters occur in ordinary lava flows. So long as the pegmatites, which appear to be closely related to the syenite intrusions, are distinctly less affected by the granulation, the author's interpretation seems open to some doubt.

Throughout the central and southern area a uniform lineation trends east-west, pitching gently east. The cause for this remarkable structure is not apparent within the quadrangle, but perhaps the mapping of all other surrounding sheets will give a clue.

The report is replete with observations that show the author's keen appreciation of structural problems. The term "vane sheet" is introduced (p. 19) to denote "sheets of intrusive material whose attitude is parallel to the linear structure of the country rock, but not necessarily concordant to the foliation, in analogy with a weather vane which rotates around an axis."

Obviously the investigation of the structure of so complicated a region as the Adirondacks will call forth various interpretations. Comments here offered aim solely at focusing attention on some points that merit special study in the future. The New York State Museum may well be proud of these recent publications.

R. BALK.

**Retrospect. An Autobiography.** By T. A. RICKARD. Pp. xi + 402, Pl. V. Whittlesey House, London and New York. 1937. Price, $3.00.

The simple statement of the title of this volume and the name of its author is enough to attract the attention of all economic geologists and mining men. The name of its author is enough to guarantee its excellence as a literary product. Mr. Rickard's name is so well known as that of the wielder of good English that it is unnecessary to say that the book he now offers to his friends will be a delight to all its readers who appreciate clear and lively writing. Some of its chapters are prose-poetry. The descriptions of the author's travels cover the world, and in them he tells what he saw in a way that keeps the interest in his discourse from flagging until the end of the volume is reached. Moreover, there are interspersed throughout the volume many comments on the history of the places described and the politics of the countries through which the traveler passed. He is outspoken in his views on English and American politics, and does not hesitate to express them frankly. Naturally, he indulges incidentally in more or less philosophy, which is of interest because the result of the broodings of an active and trained mind.

Some of the most entertaining features of the book are the brief inferences to the many prominent mining men, financiers and politicians with whom the author came in contact during his activities, and his experiences with some of them.

It will, however, be a source of disappointment to many readers that the volume is not provided with an index.

W. S. BAYLEY.

**Zum Leobener Bergmannstag 1937: Zeitschrift für das Berg-, Hütten- und Salinenwesen im Deutschen Reich,** Band 85, Heft 6, pp. 177–346, September, 1937.

Any consideration of mineral development and production in a specific European country is sure to be complicated by the boundary changes that followed the World War and the absence of data sufficiently recent to allow for such changes. To no country is this more applicable than Austria, once a partner in the Dual Monarchy and now greatly reduced in area and in population. The volume here reviewed is an excellent aid in overcoming this difficulty. It consists of a series of papers presented in 1937 at the well-known mining congress held annually at Leoben, Austria, the site of the chief Austrian School of Mines.

The subjects are varied. Several are essentially historical, dealing with mining methods of the last four centuries. Others describe concrete mining problems facing the Austrian industry and their solutions, and one gives an account of the growth of the Leoben School of Mines.

It is the remainder of the articles that should be of special interest to economic geologists. Five articles give brief but very useful reviews of Austria's important minerals, outlining their distribution and geology; these summaries deal with coal, iron, petroleum, salt, and the lesser industrial minerals, each summary having been prepared by a specialist. Space does not permit detailed reviews, but several features of interest may be mentioned. The Carboniferous hard coals of the south-Austrian Alps are briefly described. By far the chief coal reserves of Austria are brown coal, however, and these are discussed in greater detail with the aid of excellent diagrams, by Professor Petraschek of Leoben. Facts as to mining and utilization of the brown coal are also available in an article by Professor Fuglewicz, who also gives production data: the total production in 1936 was about 3,142,000 tons of coal, of which about a thirteenth is coal higher in rank than brown coal.

Petroleum was first recovered in Austria in 1930, barring negligible amounts in earlier years. It has climbed steadily, totalling 1773 cisterns in the first half of the current year, as against less than half as much in 1936. The most productive fields are the Vienna basin and the Zistersdorf region, both of which are described, together with drilling methods now in use. The Zistersdorf field and its southward extensions may well come to be one of the largest of Central European oil fields.

Of particular interest are two articles dealing with ore deposits. The excellent discussion by O. M. Friedrich concerning zoning of the ore deposits in the eastern Alps is most welcome. According to this author, the ores mentioned are referable to the central granite as exposed in the Tauern and as probably also represented by various minor cupolas, locally stripped and elsewhere covered. The process is more complicated, however, than so bald a statement suggests, and is well presented with a convenient map.

To mining geologists, the account by Herbert Holler, resident mining engineer and geologist at the famous deposits of Bleiberg, should be encouraging. The author was able to recognize definite key horizons in the ore-bearing limestone and to map these in great detail underground. The ore is richest at the junctions of fractures with specific horizons. By use of these guiding principles, not hitherto available, a saving has been effected ranging from 37 to 50 per cent in the amount of development work per ton of ore during the last few years.

All in all, this volume, with its range of subject matter, the excellence of each article, and the timeliness of the material presented, is a genuine contribution on which authors and publisher alike are to be congratulated. It fully merits careful perusal.

CHAS H. BEHRE, JR.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILLINOIS.

**The Atomic Structure of Minerals.** By W. L. BRAGG. Pp. 295; figs. 144. Cornell Univ. Press. Ithaca, New York, 1937. Price $3.75.

The author, a former Nobel Prize winner, discovered that the arrangement of atoms in crystals can be determined from their diffraction effect upon X-rays. Improvements are here described and applied to representatives of each family of crystalline minerals. The book is a discussion of newer mineralogy and is of interest not only to mineralogists but also to physicists and chemists. All of the minerals whose structures have been determined are described systematically by families, in 13 chapters, and interpretations are given of their physical properties in terms of internal atomic arrangement. The study also throws light on the chemistry of crystalline compounds. There are discussions of such problems as isomorphous replacement, polymorphism, cleavage, twinning, hardness and other physical and chemical characters of minerals. This newer study of mineralogy has been attacked from the standpoint of the physicist interested in X-ray analysis, and brings, therefore, a new viewpoint to the study of mineralogy. It is a notable contribution to the science of mineralogy.

ALAN BATEMAN.

**The Universe Surveyed.** By HAROLD RICHARDS. Pp. 722; figs. 92. D. Van Nostrand Co., New York, 1937. Price $3.50.

Scientific fundamentals relating to geology, chemistry, physics, and astronomy, are well presented in a clear style. Principles and recent discoveries are recorded in simple language for the ordinary reader and the various sciences are skillfully blended to present a clear understanding of the universe as a whole. The chapter headings give an idea of the content. They are: The Earth and its Neighbors; Consequences of Gravitation; Origin of Solar System; the Nature of Matter, Energy, Heat, and Electricity; Atoms, Atomic Structure, Chemical Transformation, and Radiant Energy; the World's Work, Materials and Communication; Geological Evolution, Weather, Geologic Processes, History of Earth, and the Frontiers of Physical Science. An appendix of 41 pages gives a review by "true-false" statements.

The book is stimulating, readable, and informative.

**Gosforth District.** By TROTTER, HOLLINGWORTH, EASTWOOD, AND ROSE. Memoirs of the Geological Survey of Great Britain, England and Wales. Pp. xii + 136. Figs. 15, pl. 6. His Majesty's Stationery Office, London, 1937. Sheet 37. Price $1.10.

A description of the geology of Sheet 37 of the "New Series" one-inch Geological Map of England covering part of the iron-ore (hematite)

field of West Cumberland, originally mapped in 1881. The area comprises the southern portion of the iron-ore field, which here is deeply buried under beds of the New Red Sandstone. In the eastern portion of the general area, however, are exposed pre-Carboniferous slates and the Borrowdale series of rhyolites, andesites, tuffs, Sedgwick's "Green Slates and Porphyries," intruded by large masses of granophyre and granite that are believed to be of Devonian age. The surface deposits are mainly boulder clays, sands, and gravels of the "Main Glaciation" and the "Scottish Readvance Glaciation." The iron-ores are believed to be the result of the metasomatic replacement of limestone along faults by downward travelling solutions. The structure of the district is outlined and its various rocks described in detail. The iron-ores are in Lower Carboniferous limestone that underlies the New Red Sandstone.

## BOOKS RECEIVED.

J. D. BATEMAN.

**Some Organic Constituents of a Recent Sediment from Chincoteague Bay, Virginia.** R. C. WELLS AND E. T. ERICKSON. Pp. 11; pl. U. S. Geol. Surv., Prof. Paper 186–D, 1937. Price, 10 cts. *Studies of sea bottom materials as possible sources of petroleum indicate some fatty acids may be present in sediments as calcium and magnesium salts.*

**Geology and Mineral Deposits of the Pilleys Island Area, Newfoundland.** G. H. ESPENSHADE. Pp. 56; figs. 6; pls. 6; maps 2. Nfld. Geol. Sect., Bull. 6. St. Johns, 1937. *General geology; pyrite deposits with copper.*

**Geology of the Sops Arm Area, White Bay, Newfoundland.** G. R. HEYL. Pp. 42; figs. 5; pls. 3; map. Nfld. Geol. Sect., Bull. 8. St. Johns, 1937. *General geology; 7 stratigraphic sections; gold prospects; marble.*

**Geology and Mineral Deposits of the Hare Bay Area, Newfoundland.** J. R. COOPER. Pp. 36; figs. 16; pls. 2; map. Nfld. Geol. Sect., Bull 9. St. Johns, 1937. *General geology; chromite, asbestos, nickel, copper, pyrite.*

**Geology and Mineral Deposits of Hawke Bay—Great Harbour Deep Area, Northern Newfoundland.** F. C. FOLEY. Pp. 24; figs. 11; pls. 2; map. Nfld. Geol. Sect., Bull. 10. St. Johns, 1937.

**Geologic Map of Texas.** Edited by G. W. STOSE. 4 sheets, each 40 by 50 in; scale 1–500,000 (8 miles to the inch). U. S. Geol. Surv., Washington. Price, $2.50. *Printed in 9 colors. Similar to the geologic maps of New Mexico, Oklahoma, and Arkansas. Prepared in cooperation with the Bureau of Economic Geology of the Univ. of Texas, societies, oil companies, and individual geologists. Prepared by N. H. Darton, L. W. Stephenson, and Julia Gardner.*

**Relief Map of West Virginia.** 31 by 35 in.; scale 8 miles to the inch. West Virginia Geol. Surv. Morgantown. Price, $1.00. *Data from U. S. Geol. Surv. Topographical Quadrangles surveyed in cooperation with the West Virginia Geol. Surv.*

**Mineral Industry for 1936.** Vol. 45. Edited by G. A. ROUSH. Pp. 771. McGraw-Hill, New York, 1937. Price, . *The usual excellent summaries and statistics.*

**Petroleum Fuels in Canada.** J. M. CASEY. Pp. 20. Can. Bur. Mines, no. 780, 1937. Price, 10 cts. *Statistical.*

**Mining Operations and Statistics, Quebec, 1935.** Pp. 122; fig.; pls. 6. Que. Bur. Mines, Ann. Rept., Part A, Quebec, 1935.

**Gold Placer Deposits of the Eastern Townships, Quebec.** H. W. MCGERRIGLE. Pp. 65; figs. 6; pl.; map. Que. Bur. Mines, Ann. Rept., Part E, Quebec, 1935.

**Preliminary Statement on the Mineral Production of the Province of Quebec for 1936.** Pp. 11. Que. Bur. Mines, Quebec, 1937.

**Geology and Mineral Resources of the Western Part of the Arkansas Coal Field.** T. A. HENDRICKS AND B. PARKS. Pp. 35; map. U. S. Geol. Surv. Bull. 847–E, 1937. Price, 25 cts. *More than 48 million tons of coal produced up to 1924 and a considerable quantity still available.*

**Manual on Geophysical Prospecting with the Magnetometer.** J. W. JOYCE. Pp. 129. U. S. Bur. Mines, 1937. Price, $1.50. *Magnetometer methods are rapid, economical, and suited particularly for reconnaissance work.*

**Eastern Part of the Sturgeon River Area.** E. L. BRUCE. **Western Part of the Sturgeon River Area.** H. C. LAIRD. **New Developments in the Little Long Lac Area.** E. L. BRUCE. Pp.150; figs. 27; pls. 38; map. Ontario Dept. Mines, Ann. Rept., vol. 45, part 2, 1936. Toronto, 1937. *Geological investigations of one of the newer Ontario gold districts.*

**Geology and Mineral Resources of the Baker Quadrangle, Oregon.** J. GILLULY. Pp. 116; figs. 7; pls. 2; map. U. S. Geol. Surv. Bull. 879, 1937. Price, 65 cts. *Placer gold.*

**Kodiak and Vicinity, Alaska.** S. R. CAPPS. Pp. 41; figs. 2; pls. 7. U. S. Geol. Surv. Bull. 868–B, 1937. Price, 25 cts. *Lode gold prospects on Kodiak Island.*

**Geologic Factors in the Interpretation of Fluorspar Reserves in the Illinois-Kentucky Field.** L. W. CURRIER. Pp. 10; fig.; pl. U. S. Geol. Surv. Bull. 886–B, 1937. Price, 5 cts. *Estimated reserves of fluorspar will last 30 to 35 years.*

**The West Nelson Earthquakes of 1929.** J. HENDERSON. Pp. 80; figs. 36. Dept. Sci. and Ind. Research, Bull. 55. Wellington, N. Z., 1937. Price, 2/. *Tremors ascribed to result of movement along the White Creek Fault.*

**Geology and Fuel Resources of the Southern Part of the Oklahoma Coal Field.** Part 1: McAlester District. T. A. HENDRICKS. Pp. 90; figs. 5; pls. 8; maps, 2. U. S. Geol. Surv. Bull. 874–A, 1937. Price, 65 cts. *Thirty-eight million tons of coal produced from Pennsylvanian formations up to 1927.*

**Geology and Mineral Resources of North-Central Chouteau, Western Hill, and Eastern Liberty Counties, Montana.** W. G. PIERCE AND C. B. HUNT. Pp. 45; pls. 7; figs. 4; map. U. S. Geol. Surv. Bull. 847–F, 1937. Price, 35 cts. *Natural gas; poor quality sub-bituminous coal; inadequate ground-water reserves.*

**The Ochre Deposits of the Riversdale District, Cape Province.** D. J. L. VISSER. Pp. 21; figs. 4. S. Africa, Geol. Surv., Bull. 9. Price, 3 d. Pretoria, 1937.

**Water-Bearing Properties of the More Important Geological Formations of the Union of South Africa.** H. F. FROMMURZE. Pp. 186; figs. 27; pls. 9. S. Africa, Geol. Surv. Mem. 34. Price, 5/. Pretoria, 1937. *Work based on records of 20,000 boreholes.*

**The Geology and Archaeology of the Vaal River Basin, Union of South Africa.** P. G. SÖHNGE, D. J. L. VISSER, AND C. VAN RIET LOWE. Pp. 192; figs. 20; pls. 36. S. Africa, Geol. Surv. Mem. 35. Pretoria, 1937. Price, 5/. *Dominantly Tertiary and Recent deposits.*

**"Wonderstone."** L. T. NEL, H. JACOBS, J. T. ALLAN, AND G. R. BOZZOLI. Pp. 44; figs. 3; pls. 5; map. S. Africa, Geol. Surv. Bull. 8. Pretoria, 1937. Price, 6 d. *"Wonderstone"—a clayey sediment derived from glassy volcanic tuff—is suitable as a structural material and electrical insulator.*

**The Pegmatite Area in Namaqualand.** T. W. GEVERS, F. C. PARTRIDGE, AND G. K. JOUBERT. Pp. 180; figs. 5; pls. 16; separate map. S. Africa, Geol. Surv. Mem. 31. Pretoria, 1937. Price, 7/6. *Beryl, scheelite, spodumene, apatite, and bismuth minerals originate in pegmatites by replacement processes.*

**Quartzstone-Waiamu Area, British Guiana.** D. W. BISHOPP. Pp. 14. Geol. Surv. Br. Guiana, Bull. 5. Georgetown, 1937. Price, 24 cts. *Placer gold.*

**Symposium on Conservation of Coal in India.** Pp. 49. Geol., Min. and Met. Soc. of India, Bull. 1. Calcutta, 1937. Price, 2 Rupees. *Proposals on coal conservation by eight contributors.*

**Asphaltos E Sapropelitos.** S. FRÓES ABREU AND R. ROQUETTE. Pp. 84. Inst. Nac. Tech., Rio de Janeiro, 1937. *Studies of pyrobituminous and asphaltic rocks as raw material for naphtha, heavy oils, and mineral wax.*

**Physical and Chemical Properties of Natural Gas of West Virginia.** P. H. PRICE AND A. J. W. HEADLEE. Pp. 223; figs. 39; pls. 12; map. W. Va. Geol. Surv., vol. 9. Morgantown, 1937.

**A Bibliography of Gold Coast Mining and Archaeology to March, 1937.** W. T. JAMES. Pp. 57. Gold Coast Geol. Surv., Bull. 9, 1937. Price, 2/.

**The Geology of the Bosumtwi Caldera and Surrounding Country.** N. R. JUNNER. Pp. 59; figs. 12; pls. 12; maps, 3. Gold Coast Geol. Surv., Bull. 8, 1937. Price, 3/–. *Includes results of a hydrographic*

*survey of Lake Bosumtwi by D. D. MacGregor and an appendix on the fossil fishes of the terraces of Lake Bosumtwi, Ashanti. Bosumtwi depression ascribed to a volcanic explosion.*

**The Geologic History of Legion State Park, Mississippi.** W. C. MORSE. Pp. 17; figs. 10. Miss. Geol. Surv., Bull. 35. University, 1937.

**Molding Sand.** G. I. WHITLATCH. Pp. 16. Tenn. Div. of Geol., Markets Circ. 5. Nashville, 1937.

**Aguas Mineraes Das Sondagens De S. Pedro, Estado De S. Paulo, Brasil.** J. BRUNO LOBO. Pp. 16; figs. 7. Serv. Geol. E Miner., no. 4. Rio de Janeiro, 1936. *Studies of artesian springs.*

**Some New Mexico Fusulinidae.** C. E. NEEDHAM. Pp. 88; fig.; pls. 12. New Mex. Bur. Mines, Bull. 14. Socorro, 1937. *Valuable index foraminifera of New Mexico, Pennsylvanian, and Permian formations.*

**The Little Bear Residuum.** F. F. MELLEN. Pp. 36; figs. 11; pl. Miss. Geol. Surv., Bull. 34. University, 1937. *Clay suitable for refractory or structural material.*

**Pyrophyllite Deposits of Manuels, Conception Bay, Newfoundland.** J. S. VHAY. Pp. 33; figs. 7; pl.; maps, 2. Nfld. Dept. Nat. Res., Geol. Sect., Bull. 7. St. John's, 1937. *Economic deposits of quartz-pyrophyllite schist amenable to beneficiation.*

**Biennial Report of the State Geologist, Missouri, 1935.** Mo. Geol. Surv., Rolla, 1935. *Results of investigations.*

**Biennial Report of the State Geologist, Missouri, 1937.** Mo. Geol. Surv., Rolla, 1937. *Results of investigations.*

**The Stratigraphy of the Upper Cretaceous Rocks North of the Arkansas River in Eastern Colorado.** C. H. DANE, W. G. PIERCE, AND J. B. REESIDE, JR. Pp. 25; figs. 3; pls. 2. U. S. Geol. Surv., Prof. Paper 186–K, 1937. Price, 10 cts. *Lower members of the Greenhorn of Kansas merge westward into the upper part of the Graneros shale of the foothills; results may have some bearing on Laramide revolution.*

## SCIENTIFIC NOTES AND NEWS

C. K. LEITH will speak over the British Broadcasting Corp. on March 24th, from three London stations at 7:10 P.M., E.S.T., in an international broadcast on "The Role of Minerals in the Present World Unrest." Professor Leith's talk is one of a weekly series on "The Way of Peace," arranged by the British Broadcasting Corporation.

M. E. JOHNSON, formerly assistant State Geologist of New Jersey, has been promoted to State Geologist.

HENRY LOUIS, professor emeritus of mining, of Newcastle-on-Tyne, is confined to his bed as the result of an accident at Stockholm last year where he was representing the Institution of Civil Engineers.

M. C. LAKE has resigned his position as geologist for the M. A. Hanna Co., in the Duluth office, and is establishing an office as consulting engineer and geologist in California. He will also supervise investigations and explorations of manganese and copper properties controlled by the Hanna Co. in the West and Southwest.

N. H. DARTON, of Washington, D. C., has been elected an honorary member of the American Association of Petroleum Geologists.

ARTHUR NOTMAN, consulting mining engineer of New York, has been elected a director of the Copper Canyon Mining Company which is operating a gold mining property in Nevada.

A. O. DUFRESNE and F. F. OSBORNE have been appointed members of the Quebec Commission of Scientific Research, which is undertaking a study of the natural resources of the Province.

H. FOSTER BAIN has left Manila and has returned to New York with his daughter.

F. H. KIHLSTEDT is consulting engineer and chief geologist for the Philippine Iron Mines at Larap, Camarines Norte.

HENRY MULRYAN, formerly geologist for the Johns-Manville Corp. in Lompoc, Calif., is now engineer and geologist in charge of all raw materials for the Southern California division of Gladding, McBean & Co.

HAROLD KINGSMILL has been elected vice-president of the Cerro de Pasco Copper Corp. and will be stationed in New York.

DAVID R. MITCHELL has been appointed professor of mining engineering and head of that department at Pennsylvania State College, School of Mineral Industries.

THE INLAND EXPLORATION COMPANY had the following American geologists in Afghanistan during 1937: Frederick G. Clapp, E. Gardner Clapp, Henry C. Rea, Howard M. Kirk, Ernest F. Fox, and Rex Vivian.

THE UNIVERSITY OF BUFFALO is completing a relief map of Niagara Falls, size 6 by 12 feet, scale 310 feet to the inch. It has been two years under construction. It depicts relief and geology and geologic history to serve as a museum exhibit.

HANS LUNDBERG, LTD., geophysicists and geologists, have removed their offices to Victory Building, Suite 604, 80 Richmond St., W., Toronto, Ont.

The AM. ASSOCIATION OF PETROLEUM GEOLOGISTS will hold its 23rd annual meeting in New Orleans, Mar. 16, 17, and 18. Exploratory equipment and methods will be displayed as usual. Concurrent meetings will be held by the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists, March 15 and 16. Six post-convention field trips are planned: (1) 2-day, Smith and Wayne counties, Miss., to study the Oligocene-Miocene problem; (2) 1-day, Lake Washington sulphur mine; (3) 1-day, Avery Island salt mine; (4) 1-day, drilling operations in Gulf Coastal waters; (5) 1-day, sightseeing trip to accessible Gulf Coastal fields; (6) airplane trip of a few hours during the convention, over the Mississippi Delta.

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